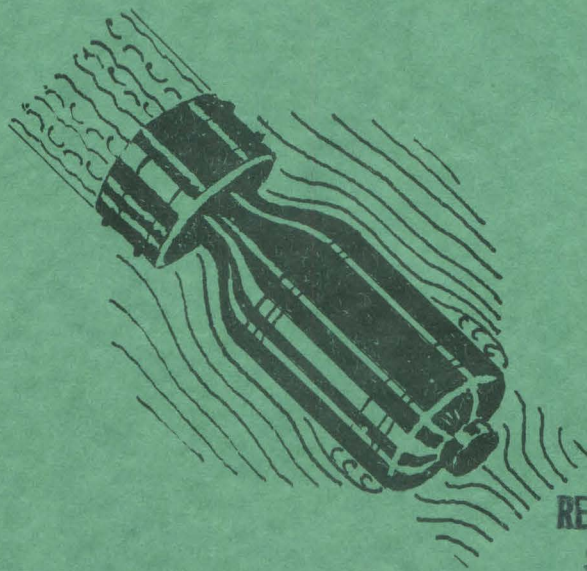


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ENTRANCE AND CAVITATION BUBBLES.



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THE HIGH SPEED WATER TUNNEL
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

SECTION N2 6.1-sr 207 1900
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ENTRANCE AND
CAVITATION BUBBLES

BY
ROBERT T. KNAPP
OFFICIAL INVESTIGATOR

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THE HIGH SPEED WATER TUNNEL
AT THE
CALIFORNIA INSTITUTE OF TECHNOLOGY
HYDRAULIC MACHINERY LABORATORY
PASADENA, CALIFORNIA

Section No. 6.1-sr207-1900
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December 27, 1944

FOREWARD

The purpose of this memorandum is to present a general discussion of the physical nature of two phenomena: (a) cavitation on underwater projectiles, and (b) the enveloping bubble formed when a projectile enters the water at moderate or high velocities. In this discussion an effort is made to demonstrate a close relationship between the two phenomena. In attempting to explain their various aspects, several hypotheses are advanced concerning the physical mechanisms involved. Although these hypotheses are founded on laboratory measurements and observations, the experimental work is far from complete. Therefore, the explanations and conclusions contained herein are very tentative, and must undoubtedly be revised extensively as the fund of experimental and analytical knowledge increases. However, it was felt that a discussion of these subjects at this time, even though it represents only a transient viewpoint, would be of value if it could serve as a stimulus for discussion and a basis for interchange of experimental information and working hypotheses.

The large number of cavitation observations and measurements which form the background of this report is the product of the combined laboratory staff. However, most of the work of compilation and analysis of the data has been carried on by H. L. Doolittle, Hydraulic Engineer. Many of the concepts set forth were arrived at in joint conferences with him and with Dr. Vito A. Vanoni. Their assistance is gratefully acknowledged.

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* TABLE OF CONTENTS

	Page
INTRODUCTION	1
CAVITATION	4
Definition of Cavitation	4
Location of Point of Inception of Cavitation	6
Cavitation Parameter	9
Degrees of Cavitation	11
Types of Cavitation	14
Effect of Cavitation on Underwater Performance	15
Gas Cycle in Cavitation	19
ENTRANCE BUBBLE	22
Comparison of Entrance and Cavitation Bubbles	22
Entrance Bubble Formation	23
Bubble Decay	24
PROJECTILE DYNAMICS WITHIN CAVITATION AND ENTRANCE BUBBLES	26
Cross Force in Bubble	26
Equilibrium Yaw Angles within Enveloping Bubbles	27
Relation between Size of Bubble and Equilibrium Yaw Angle	28
CHARACTERISTICS OF SPECIFIC NOSE SHAPES	30
Hemispherical Noses	30
Ellipsoidal Noses	31
Ogives	31
Resistance of Noses to Inception of Cavitation	34
Entrance Bubble and Cavitation Performance	
Characteristics for Successful Overall Flight	35
Selection of Nose Shape for Satisfactory	
Overall Performance	36
Spherogive Noses	36

ENTRANCE AND CAVITATION BUBBLES
AND THEIR EFFECT ON THE
UNDERWATER BEHAVIOR OF THE PROJECTILE

INTRODUCTION

An "air-water" projectile, such as an aircraft torpedo, in the course of its trajectory from the airplane to the underwater target, passes through at least one, and possibly two, transient conditions in which its entire performance may be affected significantly by phenomena involving both a gas and a liquid. The first of these begins at the instant of water impact, and continues as long as the air that has been carried down into the water by the projectile stays with it as a bubble that covers at least a portion of the projectile's surface. The second condition occurs if, during the subsequent underwater run, the reduction of pressure resulting from the velocity of the body becomes, at any point on the projectile, equal to the vapor pressure of the water at the existing temperature. If this happens, evaporation will occur at this point, forming a vapor-filled bubble. This method of formation of vapor bubbles is called "cavitation". In the past the general approach has been to treat these two phenomena as being unrelated. The objective of this memorandum is to point out that they are both manifestations of the same basic phenomenon and to discuss this phenomenon in some detail, including an analysis of the similarities and the differences between these two manifestations.

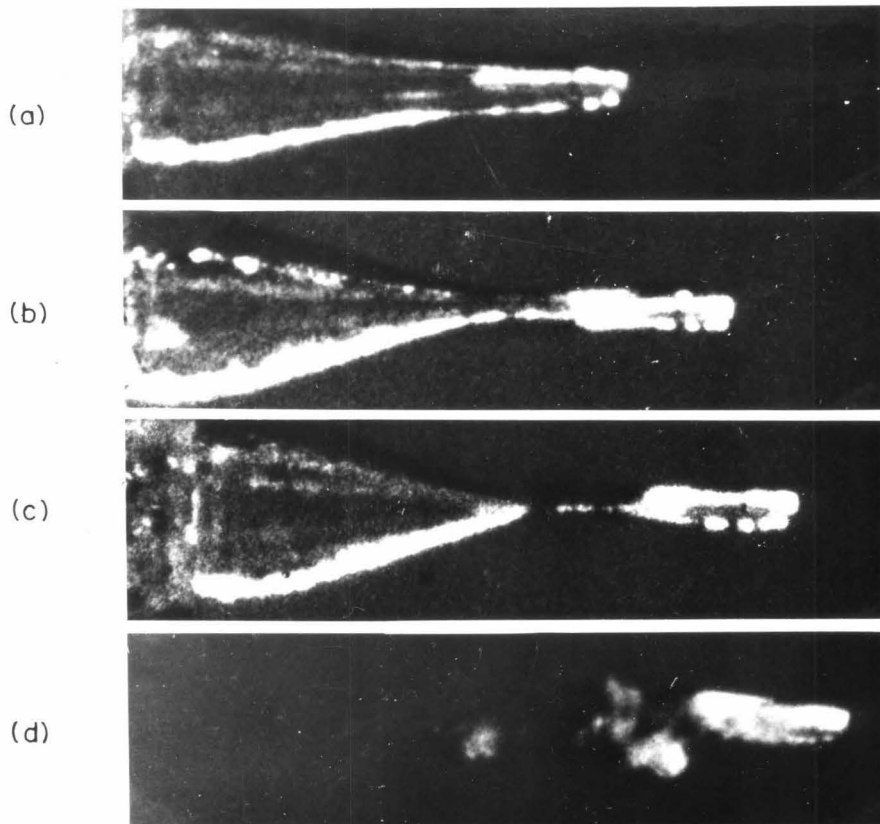
As a projectile, having a moderate or high speed, first touches the surface of the water, the latter is forced away from the point of contact. This action is so violent that it gives rise to the common description that the projectile "blows a hole for itself in the water". This cavity may be considerably larger in diameter than the projectile, and many times its length. During its formation it is open to the atmosphere and, therefore, is filled with air at or slightly below atmospheric pressure. As the projectile penetrates farther into the water, the cavity continues to lengthen until a point is finally reached when the water closes in, severing the connection between the cavity and the atmosphere, and changing the cavity from an open tube into a closed bubble. This bubble continues to travel forward with the projectile. However, from the instant of closure the amount of air within the bubble diminishes because it is entrained and pumped

away by the water through which it is moving, until it finally disappears completely. Figure 1 (a), (b), (c), and (d)* shows such a cycle. This cavity, from the instant of its inception as the tip of the projectile first touches the water, until its final disappearance as the last particle of air is swept away from the surface of the projectile, is commonly referred to as the "entrance bubble".

As the projectile touches the water the drag goes up tremendously, primarily because of the great increase in density of the water over the air; and secondarily because, as far as the water is concerned, the shape of the projectile is that of the entrance bubble, and this in general is less "streamlined" than the projectile, and thus has a higher form drag, as well as a larger cross section. Furthermore, the entire force distribution on the body is radically altered. During the air flight, the aerodynamic forces are the result of the skin friction and the pressure distribution over the entire body; whereas, in the entrance bubble the only existing forces of significant magnitude are applied in the very small areas of contact between the projectile and the water. In the initial stages of the bubble formation, the nose is the only point of contact. Hence, the point of application is ahead of the center of gravity, and for any normal nose shape the condition is unstable. The lateral component of this force acts to produce a rotation about a transverse axis through the center of gravity, and this rotation continues until a restraining force is developed when the afterbody or tail structure comes in contact with the wall of the bubble. Since all of these forces are large, they greatly affect both the velocity and the direction of the motion of the projectile.

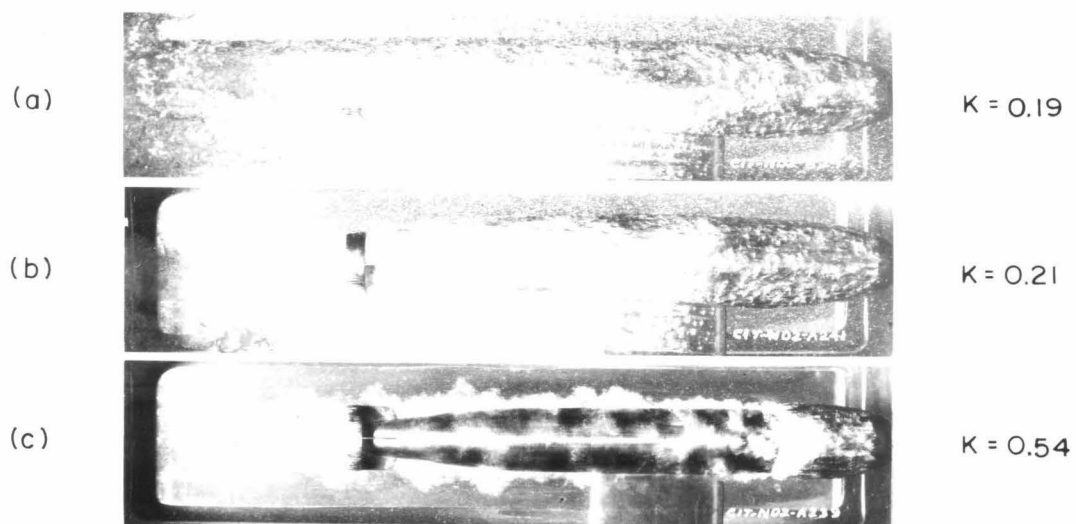
The entry bubble is an air bubble, and although there may be traces of water vapor or other gases present, they play no significant part in the phenomenon. On the other hand, cavitation involves only water and water vapor. Again, there may be traces, say, of air and carbon dioxide present, but they have no significant effect on the cavitation. Thus, true cavitation occurs only on a completely submerged body from which the entrance bubble has been entirely removed. It is also a bubble phenomenon, but in this case, the bubble is filled with water vapor obtained by evaporating part of the adjacent liquid. However, this bubble has many of the properties of the entrance bubble. In general, it increases the drag coefficient of the projectile by increasing its effective diameter and by decreasing its degree of streamlining. It changes the distribution of forces, since again, no force of significance acts on that part of the skin of the projectile that is within the bubble. In either case, if the bubble envelops the control and stabilizing surfaces, they become ineffective. These and other superficial similarities may be readily recognized in the comparison of the cavitation bubbles, shown in Figure 2, with the entrance bubbles of Figure 1.

*These pictures were taken in the model tank at the Naval Ordnance Laboratory, Washington.



ENTRANCE BUBBLE CYCLE FROM MODEL TANK

FIGURE 1



CAVITATION BUBBLES

FIGURE 2

CAVITATIONDEFINITION OF CAVITATION

In this discussion cavitation will be taken to mean the generation of a gas space, or bubble, in a liquid, this space being filled primarily with the gas phase of the liquid, at the same temperature as the liquid, and at the equilibrium pressure for that temperature. So far all of these requirements could be filled by gas bubbles formed in a boiling liquid. This is not surprising, since the cavitation voids are filled with gas by evaporating a portion of the surrounding fluid, i.e., by boiling. However, in the case of a normal boiling liquid, it is either stationary with respect to the container or moving at velocities so low that they have no appreciable effect on the pressure. Thus, the pressure is sensibly the same throughout the liquid, varying only with the depth. In cavitation, however, the velocities in the cavitating zone must be high, because they are the cause of the drop in pressure from the static pressure, which is well above vapor pressure, down to vapor pressure itself at the point where the cavity is formed. This drop in pressure which accompanies an increase in velocity is an accordance with the principle of the conservation of energy, as expressed in the Bernoulli equation. Consider a stream tube in the flow pattern in Figure 3. If the Bernoulli equation is written between Points 1 and 2, which lie in a horizontal plane, it becomes

$$p_1 + \rho \frac{V_1^2}{2} = p_2 + \rho \frac{V_2^2}{2}$$

or

$$p_2 = p_1 + \frac{\rho}{2} (V_1^2 - V_2^2)$$

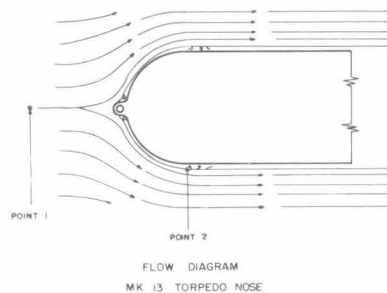


FIGURE 3



FIGURE 4 - CAVITATION DAMAGE ON PUMP RUNNER

Another striking difference between the cavitation phenomenon and normal boiling is seen when the possibility of collapse of a vapor bubble is examined. In the boiling liquid a gas bubble, once formed, tends to rise due to its buoyancy, and as it rises, the pressure on it decreases due to the decreasing hydrostatic head. Thus, even though no more vapor passes into the bubble, it will expand until it reaches the surface. Now, a vapor bubble formed by cavitation will also tend to rise due to buoyancy. However, in most cases, the upward velocity due to the buoyancy is so very small compared to the velocity of flow of the surrounding liquid that it is negligible. Therefore, the path of the bubble is determined by the flow of the liquid. If the liquid carries the bubble to a region where the pressure is higher, the bubble will collapse because the vapor is no longer in equilibrium with the liquid, i.e., it condenses. Since in this condensation the vapor disappears entirely into the liquid phase, there is no gas to cushion the collapse. Therefore, when the liquid surfaces meet or when a liquid surface collapses against a solid surface forming a part of the bubble boundary, the "water hammer pressure" which results can be extremely high. These high forces are probably responsible for the pitting of metal surfaces that is commonly associated with continued cavitation. An extreme case of cavitation damage on the runner of a centrifugal pump is shown in Figure 4. However, the principal objective of this discussion is to investigate the phenomenon of cavitation itself and not the damage resulting from it. Therefore, cavitation damage will be given no further consideration.

LOCATION OF POINT OF INCEPTION OF CAVITATION

From the preceding description of the nature of cavitation, it is obvious that if the pressure distribution is known, then the point of cavitation inception can be determined immediately. Cavitation will obviously occur first at the point of minimum pressure on the body. It will commence when this pressure reaches the vapor pressure of the fluid. If the surface of the submerged body be thought of as a deflecting or guiding surface for the flowing fluid, a rough estimate can be made of the critical points on the body where low pressures might be expected. Thus, parts of the surface which deflect the flow away from the body will be regions of high pressure and, therefore, will not be susceptible to cavitation. Conversely, those parts of the surface which fall away from the flow and thus deflect it so that the flow lines are concave toward the body are low-pressure regions, and hence zones in which cavitation may be expected to appear. Consider a typical projectile, such as the torpedo shape which is shown, together with its pressure distribution in Figure 5. The tip of the nose is always the high-pressure region because it is deflecting the flow away from the body. However, considerably before the cylindrical portion is reached, the nose surface is falling away from the lines of flow, and hence, a low-pressure region can be anticipated. If cavitation occurs in this region, as shown in Figure 6, it is usually referred to as nose cavitation. The amount of lowering of the pressure below that of the neighboring undisturbed liquid is, for a given velocity, determined by the shape of the nose. It is to be expected that the cylindrical part of the body will be a zone of rather uniform pressure since it has no means for causing any radical change in the flow direction. However, as soon as the body starts to decrease in diameter towards the tail, another low-pressure region will be formed. If this has a lower pressure than the corresponding region on the nose, cavitation will first occur here, as in Figure 7. Finally, a high-pressure zone can be expected toward the aft end where the flow lines that follow the tapering afterbody come together and are forced to lose their radial component of velocity.

If the body has fixed or movable fins, the leading edges will be high-pressure regions. However, by analogy to the flow around the nose, these edges will be followed immediately by low-pressure regions, and hence, as in Figure 8, will be another possible source of cavitation. If the projectile is a torpedo, the propellers will offer another possible location for cavitation, as seen in Figure 9; a very likely one in fact, because they are nothing more than moving fins, and their rotation means that they have a higher velocity with respect to the water than do the fins. This higher velocity may result in correspondingly lower pressures, and hence, additional cavitation regions. It is possible to conceive of a body so designed that each of these four zones would have the same pressure and hence, when the pressure field was lowered they would all reach vapor pressure at the same instant, and four independent zones of cavitation would be formed. Figure 10 shows a body upon which cavitation starts in several different zones at nearly the same time. In practice, however, this is

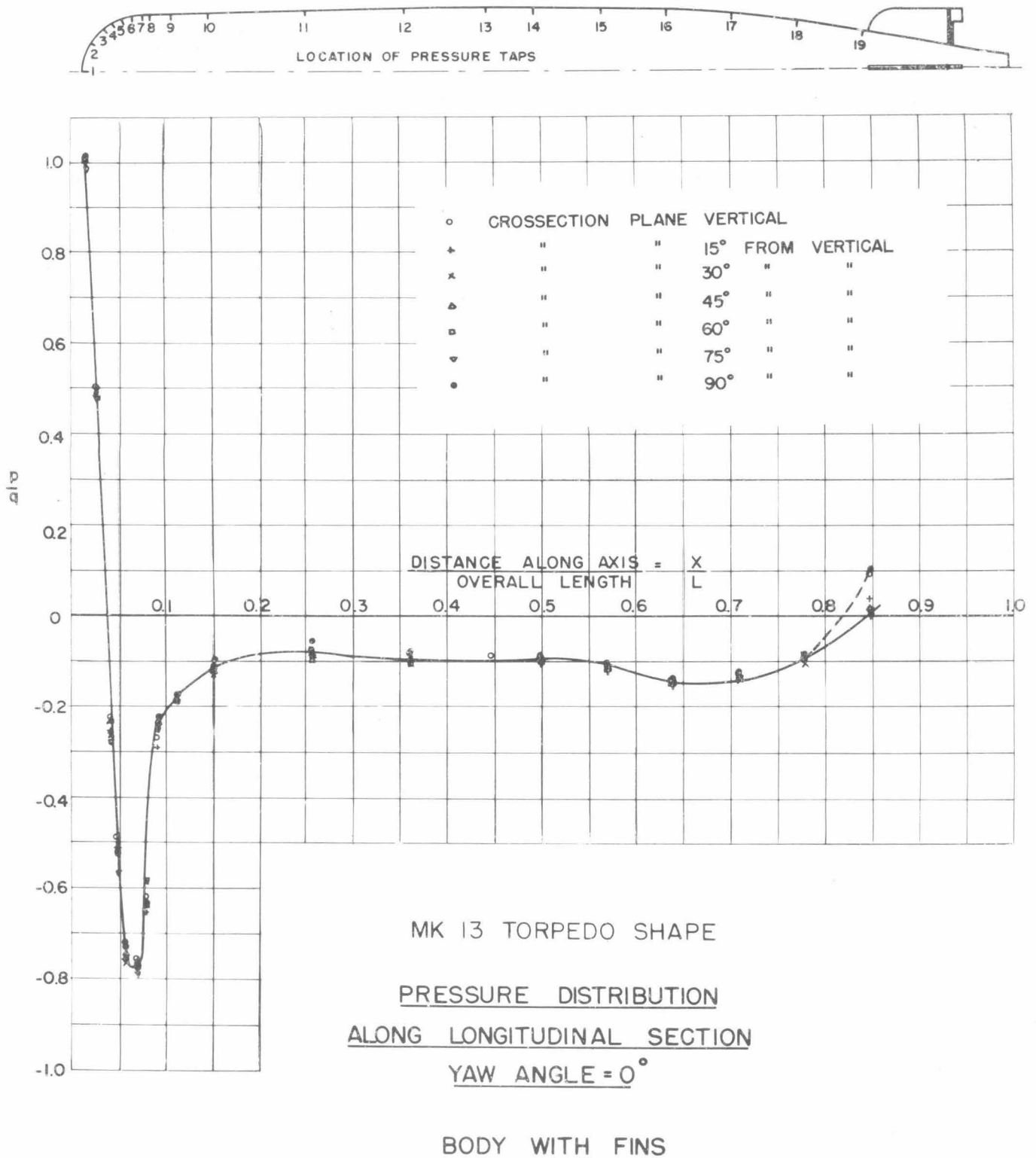


FIGURE 5

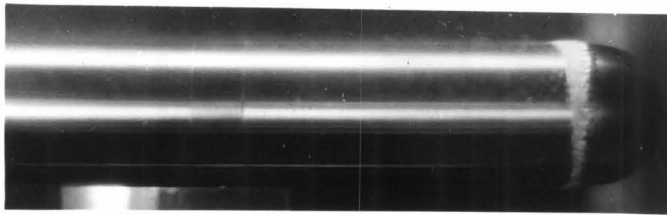


FIGURE 6 - NOSE CAVITATION

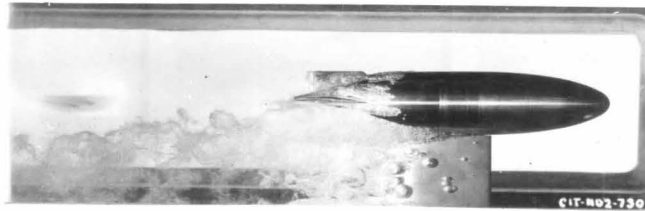


FIGURE 7 - AFTERBODY CAVITATION

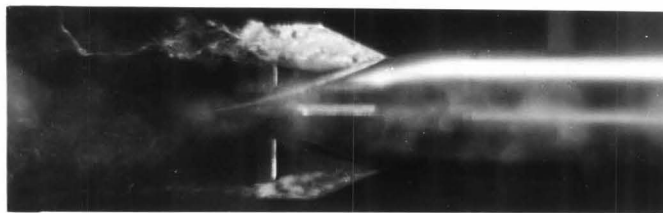


FIGURE 8 - FIN CAVITATION

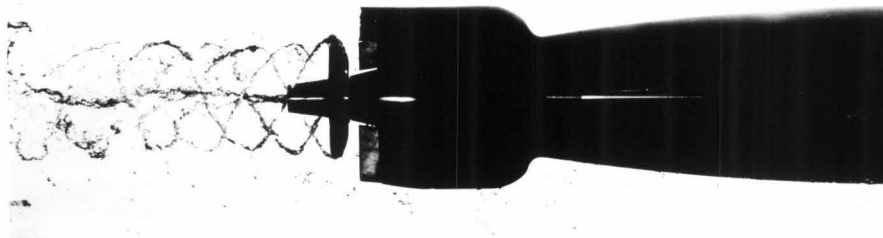


FIGURE 9 - PROPELLER CAVITATION

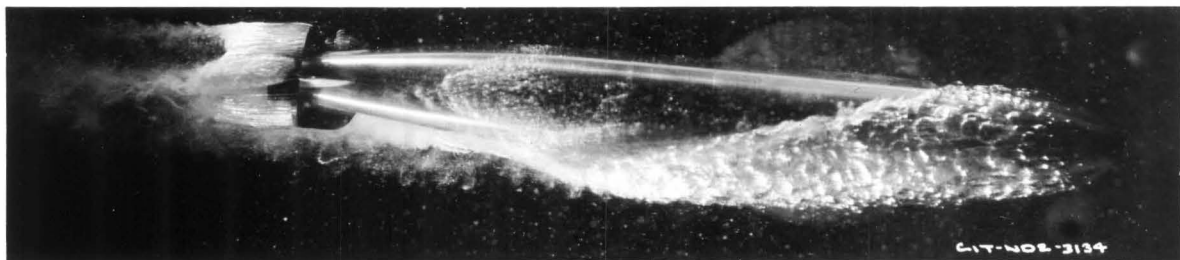


FIGURE 10 - BODY WITH SEVERAL POINTS OF SIMULTANEOUS CAVITATION

rarely the case. One zone usually has a lower pressure than the other and cavitation becomes evident there first. If the pressure field continues to drop, the zone of next lowest pressure will start to cavitate, and so on. Often, however, the growth of the cavitation bubble at the first zone is so rapid that it envelops the other zones before they would have reached cavitation conditions if the flow had remained undisturbed. This growth of the bubble will be discussed in more detail later in the report.

CAVITATION PARAMETER

In order to describe quantitatively the conditions under which cavitation occurs, the cavitation parameter, K , has been defined as follows:

$$K = \frac{p_L - p_B}{\rho \frac{V^2}{2}} \quad (1)$$

in which

p_L = absolute pressure in the undisturbed liquid

p_B = absolute pressure in the bubble or cavity

V = velocity of the projectile with respect to the undisturbed liquid

ρ = density of liquid

Note that any homogeneous set of units can be used in the computation of this parameter. Thus, it is often convenient to express this parameter in terms of the head, i.e.,

$$K = \frac{h_L - h_B}{\frac{V^2}{2g}} \quad (1a)$$

where

h_L = the submergence plus the barometric head, ft of water

h_B = absolute pressure in the bubble, ft of water

g = acceleration of gravity, ft/sec²

It will be seen that the numerator of both expressions is simply the net pressure acting to collapse the cavity or bubble. The denominator is the velocity pressure. Since the pressure reduction at any point on the body is proportional to the velocity head, it may be considered that the velocity head is a measure of the pressure available to open up a cavity. From this point of view, the cavitation parameter measures the ratio of the pressure available to collapse the bubble to the pressure available to open

it. If the K for incipient cavitation is considered, it can be interpreted to mean the maximum reduction in pressure on the surface of the body, measured in terms of the velocity head. From this it follows that, if a body starts to cavitate at the cavitation parameter of one, it means that the lowest pressure at any point on the body is one velocity head below that of the undisturbed fluid. Figure 5 presents a concrete example of this relationship. It shows the measured pressure distribution on the surface of a torpedo, calculated in terms of the velocity head. The lowest pressure occurs at the junction between the spherical nose and the conical section. The pressure at this point is 0.8 of a velocity head below that in the undisturbed fluid. Under cavitation tests in the Water Tunnel, this same shape cavitates first at this exact location, and the measured K for incipient cavitation is 0.8.

It will be seen that the K for incipient cavitation is a measure of the resistance of the body to cavitation, or in other words, an indication of the excellence of the shape. Thus, the lower the K for incipient cavitation, the greater the cavitation resistance, and the better the shape from this viewpoint.

It should be borne in mind that the cavitation characteristics of a given body are not defined by a single value of K . For example, a specific torpedo shape might show signs of incipient cavitation on the nose at a particular value of K . With a slightly lower value, K_2 , cavitation might commence on the fixed fins. Careful examination of the propellers might demonstrate that cavitation had commenced on them at a value, K_3 , which was even greater than K_1 . A value, K_4 , might be recorded at the start of cavitation on the afterbody. At K_5 , the length of the cavitation bubble on the nose might be observed to be equal to two body diameters.

The preceding paragraphs illustrate the fact that the cavitation parameter, K , has many uses. Two of these should be noted explicitly. The first one is that for a given projectile, each specific bubble configuration from the point of inception to the development of a bubble of "infinite" length corresponds to a specific value of K . It thus serves to define, for one given shape, the degree of cavitation. The second use is that in comparing different projectiles or different parts of the same projectile, it serves as a yardstick for the evaluation of their relative performances. This use has been demonstrated in the two preceding paragraphs.

It may have been noted that in defining the cavitation parameter there has been no discussion concerning what determines the pressure within the bubble. This was done deliberately because the pressure in the bubble may be determined by a number of different factors which have no effect on the interpretation of the parameter. Thus, it is quite immaterial whether the bubble contains air under pressure, products of combustion, or water vapor in equilibrium with the surrounding water. However, if the cavitation void is filled only with water vapor in equilibrium, then

-11-

the phenomenon is that of "true cavitation" as normally defined. In this case, p_B becomes the pressure of the vapor, which can be determined from tables of the vapor pressure of sea water or fresh water, as the case may be. Figure 11 has been constructed to assist in the determination of K for such cases. This diagram clearly shows the effect of depth, or submergence, and velocity.

It should be noted that although under service conditions, the pressure on the water surface can only vary by the normal barometric fluctuations, very different conditions can be established in the laboratory, where, for example, the "atmospheric" pressure is completely under control. Thus, in the High Speed Water Tunnel, shapes can be made to cavitate at much lower velocities than would be possible in the free ocean, simply by reducing the system pressure until the K is reached at which the desired degree of cavitation is obtained. For example, take the case of a projectile which runs in the ocean at 5 ft submergence and has a K for incipient cavitation of 0.45. The velocity at which cavitation commences is given by Equation (1a).

$$V = \sqrt{\frac{2g(h_L - h_B)}{K}} = \sqrt{\frac{64.4 (33.2 + 5 - 0.4)}{0.45}} = 73.8 \text{ ft/sec*}$$

If a model of this projectile is tested in the Water Tunnel, and if the tunnel pressure, h_L is reduced, say, to 15 ft absolute, the velocity for incipient cavitation reduces to

$$V = \sqrt{\frac{64.4 (15 - 0.4)}{0.45}} = 45.7 \text{ ft/sec}$$

A further reduction of h_L to 5 ft absolute, would cause the cavitation to start at 25.6 ft/sec, or, if the velocity were maintained at 45.7 ft/sec, would reduce the K to 0.14. This would produce extremely heavy cavitation, resulting in a bubble several times as long as the projectile.

DEGREES OF CAVITATION

One of the most significant cavitation characteristics of a body is its K for incipient cavitation. However, this by no means describes its entire cavitation performance even if consideration is given only to the single zone in which cavitation first commences. For example, Figure 12 (a) to (g) represents the development of cavitation on a typical body with a hemispherical nose. It will be observed that as the cavitation parameter decreases, the cavitation zone lengthens. It has been found in the laboratory that for a given shape of body and constant yaw angle, the relationship between the length of the zone and the value of K is a fixed function of that shape, thus, as suggested earlier in this section, K can be used to describe the degree of cavitation as well as the beginning of it.

Since, for a given value of K , the cavitation bubble has a fixed size and location with respect to the body, from the point of view of the fluid the shape of the body has been altered by it.

*33.2' of sea water at 50°F = 1 atmosphere. At this temperature its vapor pressure is 0.4 ft.

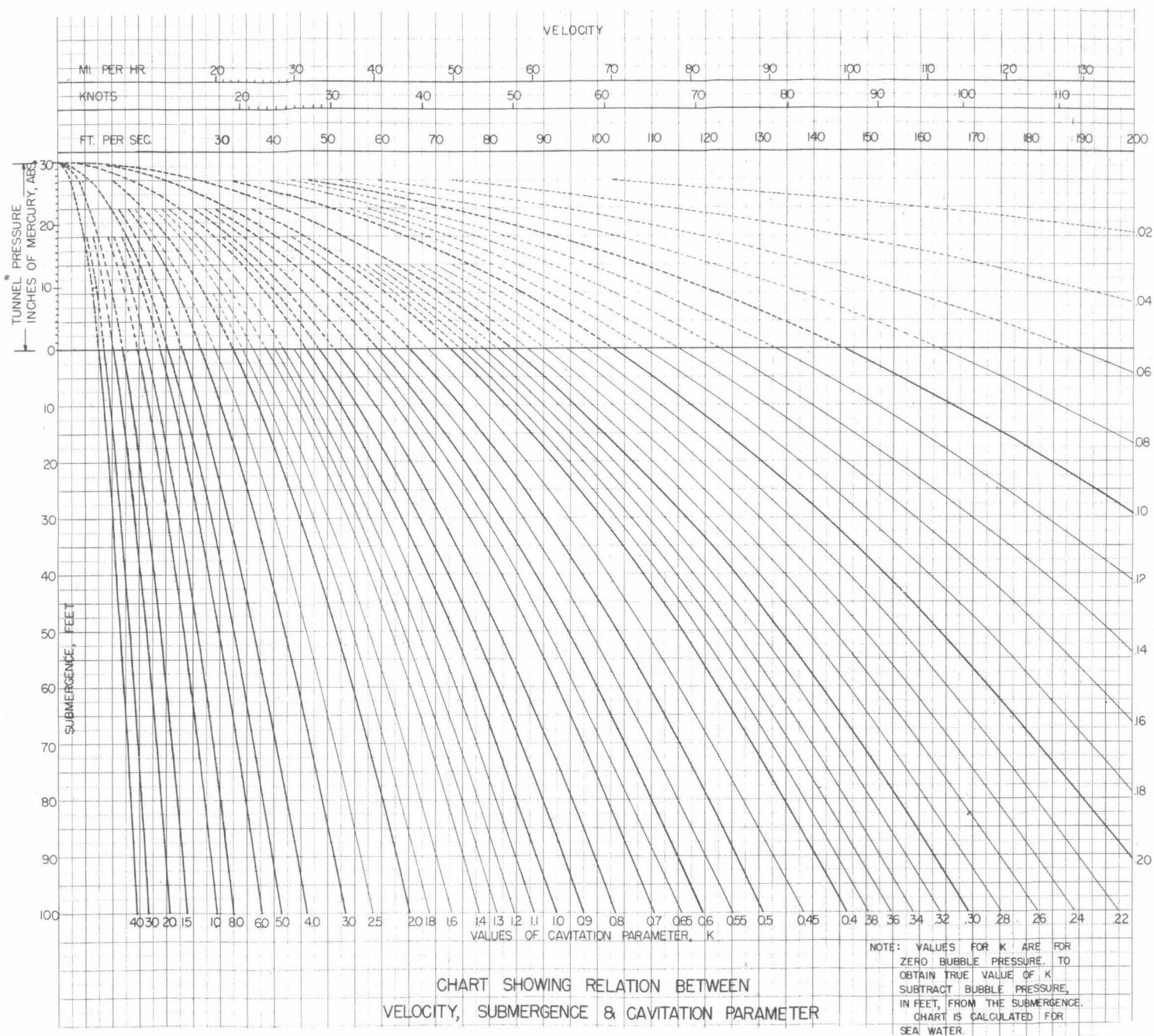


FIGURE 11

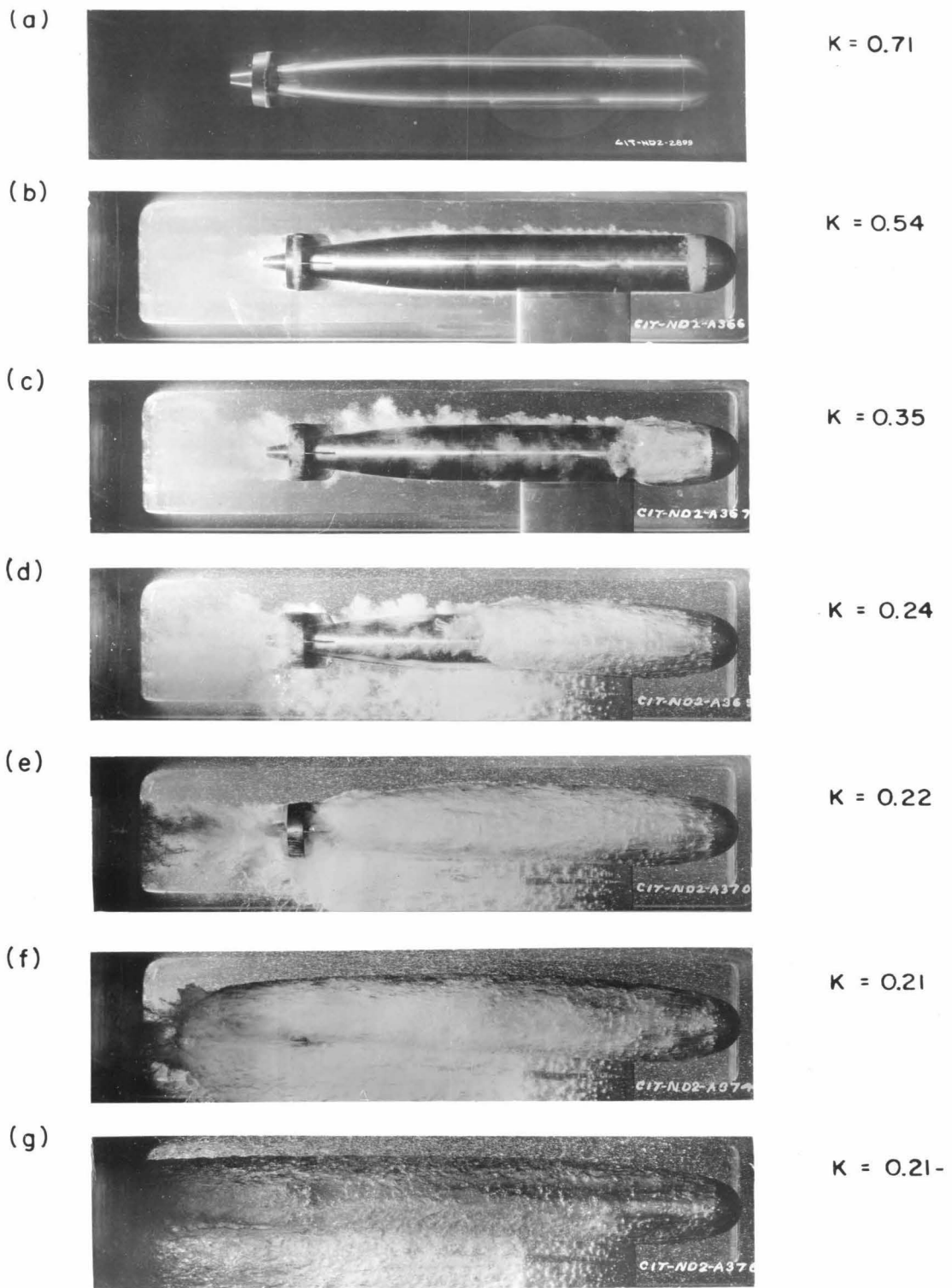
Thus, as far as the fluid is concerned, it is flowing around an object which has the overall shape of the original body plus the cavitation void. Therefore, each change in shape of the bubble produces corresponding changes both in the velocity and the pressure fields surrounding the body. Another way of saying this would be that each value of K corresponds to a given effective body shape. However, there is one unique characteristic of the part of the effective body that is formed by the bubble. The original solid body was unaffected by a variation in pressure on it, i.e., the variation in pressure produced no change in the body shape. However, the bubble is incapable of resisting any appreciable difference in pressure over its surface. In other words, the pressure on the entire surface of the bubble must be uniform since in case it is not, the bubble will deform until it is. Thus the interface between the bubble and the liquid is an isopiestic surface.* From this it might appear at first sight that if the pressure distribution around the body is measured or computed, the isopiestic surfaces would define the shape and course of growth of the cavitation bubble. This is not true, as indicated by the previous discussion, due to the changes in the pressure fields produced by changes in the bubble shape. However, it is reasonable to suppose that for a given state of development of the cavitation bubble, the adjacent isopiestic surface in the flow will be a good indication of the direction of growth of the bubble as the pressure is dropped.

Cavitation is often thought of as a very localized phenomenon which occurs in narrow zones such as those shown in Figure 12, (a) and (b). However, as seen in Figure 12 (c) to (g), if the pressure is reduced sufficiently, the cavitation grows to enormous proportions and may become many times the volume of the original body. This complete envelopment of a projectile by a vapor or a gas bubble is easily possible if the velocity is high enough or if the pressure in the bubble is sufficiently great. Thus, in Figure 12 (g) it is seen that only a portion of the hemispherical nose of the body is in contact with the water. The flow breaks away from the body before the full diameter of the projectile is exposed. This is, of course, a typical bubble condition which occurs when the projectile enters the water from the air.

TYPES OF CAVITATION

If a shape, having a relatively poor cavitation resistance, as for example, a hemispherical nose, is studied, it will be observed that when cavitation commences it occurs in a sharply defined zone. It appears as a white band, which, upon closer examination seems to be made up of a series of very small bubbles. As the pressure is lowered and the cavitation zone spreads, the zone remains quite sharply defined, especially at the leading edge, and the character of the surface stays approximately the same. This might be called "fine-grained cavitation". A typical

*This statement ignores the minute pressure gradient that may exist due to gas circulation in the bubble. For a discussion of this factor see Page 19.



DEVELOPMENT OF CAVITATION BUBBLE
HEMISPHERICAL NOSE

FIGURE 12

-15-

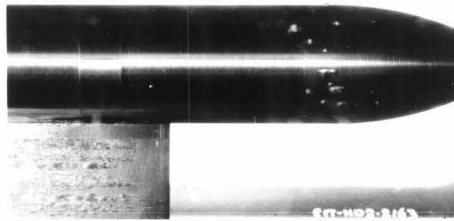
case of this type is seen in Figure 12. In contrast to this, if a shape having good cavitation resistance is subject to a similar scrutiny, as, for example, a long elliptical or ogival nose, cavitation will be evidenced first by the formation of a series of individual and comparatively large droplike bubbles. As the pressure is reduced, these bubbles grow more numerous until they cover the entire surface, but they retain their individual character over a wide range of cavitation conditions. This might be termed "coarse-grained cavitation". A characteristic example of this class is seen in Figure 13 (a) to (c), which shows cavitation development on an ogive, whose radius of curvature is equal to 2.0 body diameters.

One possible explanation of the reason for the difference in the appearance of these two variants of the cavitation phenomenon may be found in an examination of the pressure distribution occurring on the two shapes. In the case of the hemispherical nose the pressure gradient is relatively steep, and therefore, the zone in which the pressure becomes equal to the vapor pressure is quite sharply defined. Consider two elements of liquid moving abreast in parallel paths along the body. Both enter the cavitation zone at the same instant so that there is no time available for the change in flow produced by the presence of the gas bubble formed in one element to affect the pressure, and hence the evolution of gas in the adjacent element. Therefore, cavitation occurs simultaneously in the two elements, and consequently around the entire circumference of the nose. On the other hand, on the long ogive nose, the pressure gradient is much smaller. Therefore, the exact point on the path of the liquid element at which the pressure reaches the vapor pressure is much less sharply defined. Thus, it is possible to imagine that, due to localized fluctuations in velocity that are always present in turbulent flow, or possibly in some instances due to a minor surface imperfection, such as a scratch on the body, one element of the fluid would reach the vapor pressure slightly before the corresponding one on the neighboring parallel path. The resulting gas bubble would cause the liquid to be deflected around it, which might result in a slight increase in pressure on the liquid in the adjacent element and thus delay vaporization from it until it has moved a short distance further downstream. This explanation is very tentative and is offered without any background of quantitative experimental confirmation.

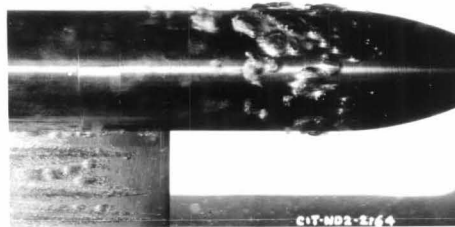
EFFECT OF CAVITATION ON UNDERWATER PERFORMANCE

Comparatively little quantitative information is available about the effect of cavitation on the performance of underwater projectiles. An exception to this statement must be made in the case of propeller cavitation, since much study and analysis has gone into the investigation of the effect of cavitation on propeller performance. For further details reference should be made to the publications of the David Taylor Model Basin, the Department of Naval Architecture at the Massachusetts Institute of Technology, etc.

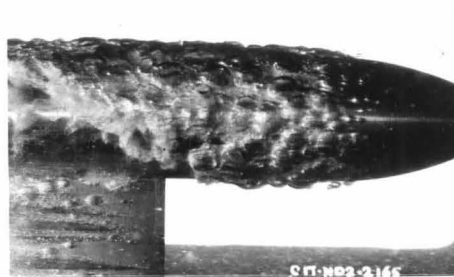
(a)

 $K = 0.31$

(b)

 $K = 0.25$

(c)

 $K = 0.18$

COARSE GRAINED CAVITATION
2 CALIBER RADIUS OGIVE

FIGURE 13

-17-

The presence of the cavitation bubble on the main body of the projectile would be expected to modify the normal hydrodynamic forces of drag, cross force, and moment. The nature and magnitude of these effects are discussed together with those of the entrance bubble, beginning on Page 26. However, there is one effect, probably peculiar to the inception of true cavitation, that will be mentioned here. There is some evidence to indicate, on certain body shapes, that there is a very small reduction in drag just before or during the inception of cavitation. However, this seems to be followed by a quite rapid increase in drag as the cavitation zone develops to an appreciable magnitude. If the normal division of the total drag into skin friction and form drag is considered, it is not very difficult to find an explanation for this anomalous behavior. It would be expected that the presence of the cavitation bubble would affect the two components of the drag in opposite manners. The skin friction should be reduced, since the total area of the projectile exposed to the flow of the liquid is decreased. Furthermore, the first traces of cavitation may possibly inhibit the growth of the boundary layer. Presumably, however, the form drag should be increased, since it would be a rare case indeed in which the presence of the bubble could be expected to improve the hydrodynamic form of the body enough to overbalance the increase in drag which would result from the larger effective diameter due to the presence of the bubble. Through the interplay of these two opposing effects, it is possible that at the inception of cavitation, the skin friction is reduced more than the form drag is increased; whereas, as the cavitation develops, the increase in form drag overtakes and then completely masks the reduction of skin friction. Figure 14 gives the results of a drag test which shows this effect.

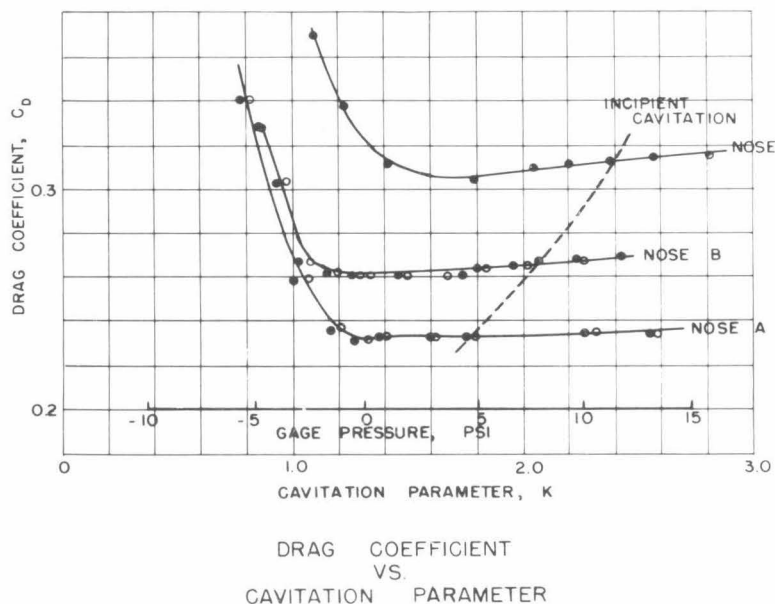


FIGURE 14

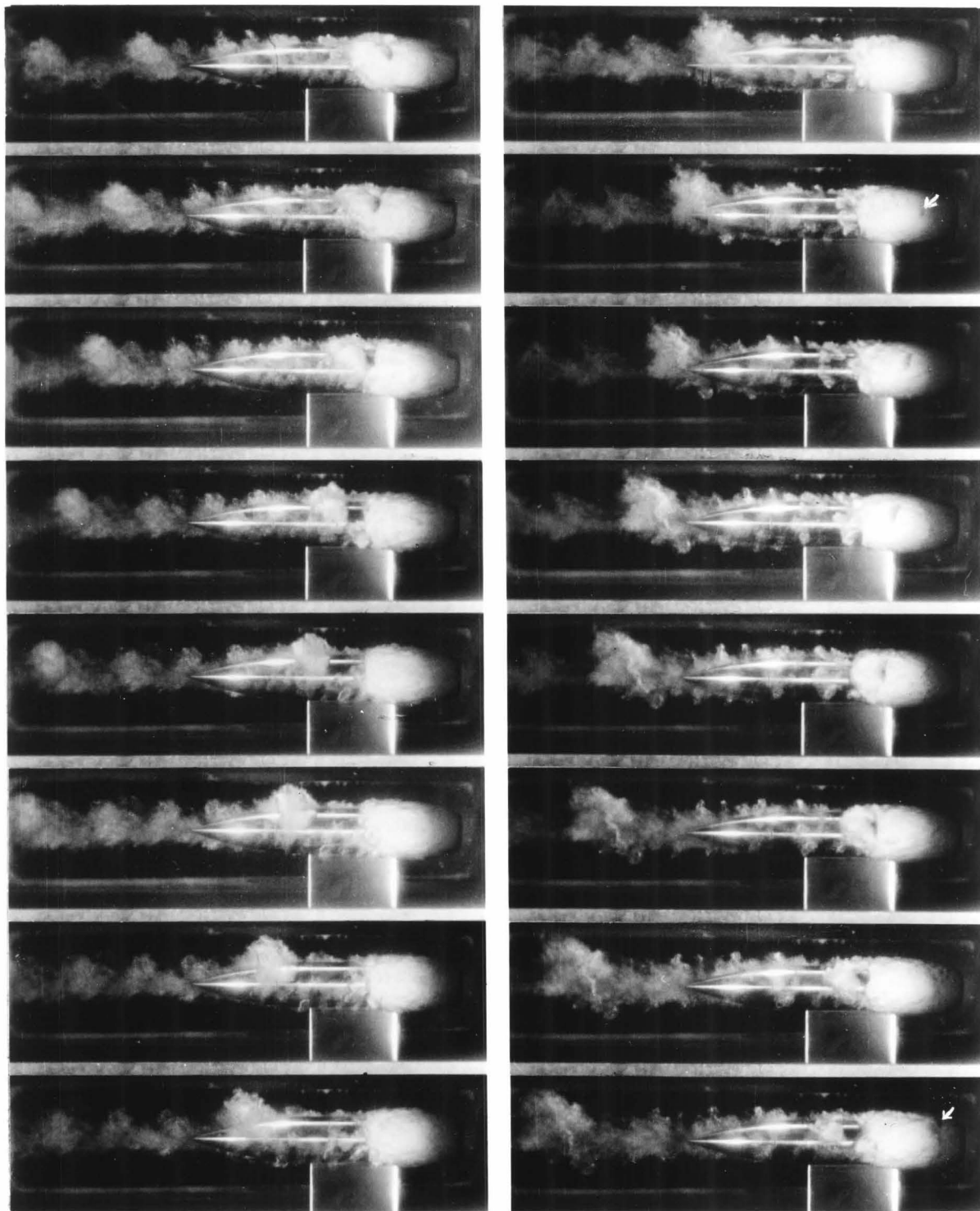


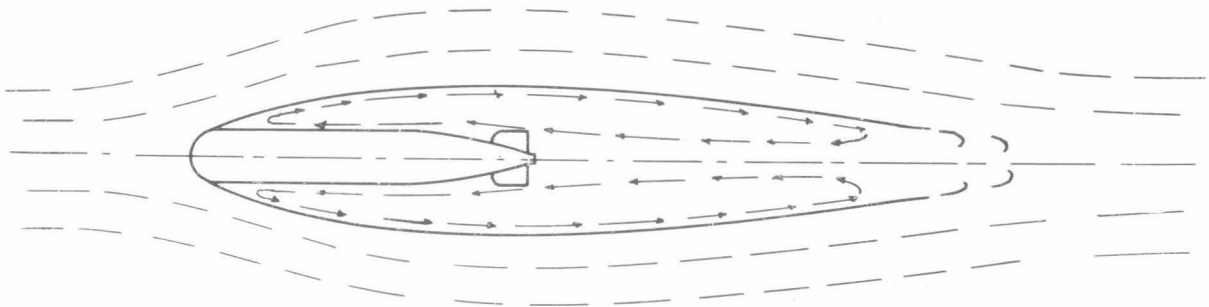
FIGURE 15

ENTRAINMENT FROM CAVITATION BUBBLE

Flow velocity 60 ft/sec. Interval between pictures approximately $1/750$ second. Note arrows showing beginning of second and third breaks.

GAS CYCLE IN CAVITATION

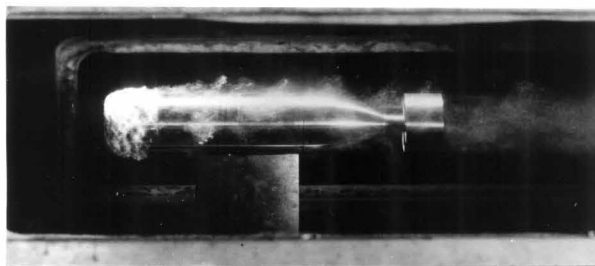
In general, little attention has been paid to the behavior of the vapor which fills a cavitation bubble. For many purposes it has been adequate to consider the space as if it were a complete vacuum. Actually it is gas filled. That part of the surface which is bounded by the liquid is moving rapidly with respect to the gas. The gas is produced by vaporization of the liquid through this interface. Since the heat for this vaporization comes from the sensible heat of the liquid itself, the process must result in a decrease in temperature of the liquid. As the percentage of liquid that is vaporized must be extremely small, this decrease in temperature is probably negligible for any of the present considerations. It might be assumed that the downstream boundary of the cavitation zone is a region of condensation where the vapor collapses back to the liquid state. However, observation of actual cavitation quickly shows that, although this may be partially true, it does not completely describe the phenomenon. The downstream end of the cavitation zone can be seen to be a region of very rapid entrainment of elements of the gas by the rapidly moving liquid. This is especially evident in photographs taken with very short duration flash illumination. In such pictures it is possible to see not only clouds of minute bubbles being swept far downstream from the end of the cavitation zone, but large individual bubbles can be observed in the process of entrainment and transportation downstream. All of the cavitation photographs presented here are taken with such flashes which give a resulting exposure time between 1 and 25 microseconds. Figure 15 shows this entrainment quite clearly. Furthermore, within the main cavitation bubble there must be a rather intense circulation of the gas, since a large part of the surface is formed by the moving liquid, which must induce a corresponding flow in the gas. Since all of this gas cannot be entrained at the downstream end, there must be a resulting forward counter flow along the surface of the projectile to complete the circulation, as shown on the sketch in Figure 16. It is probable that one result of this circulation pattern is that there is a minute pressure difference which exists between the upstream and downstream end of the bubble, the higher pressure being, of course, at the upstream end.



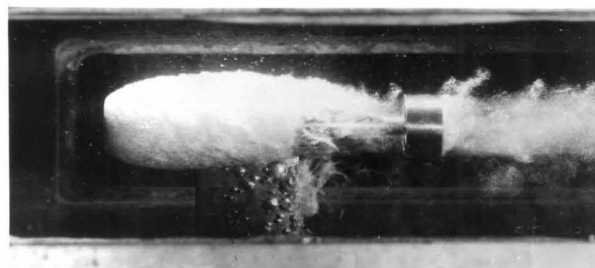
GAS CIRCULATION WITHIN BUBBLE

FIGURE 16

(a)

 $K = 1.05$

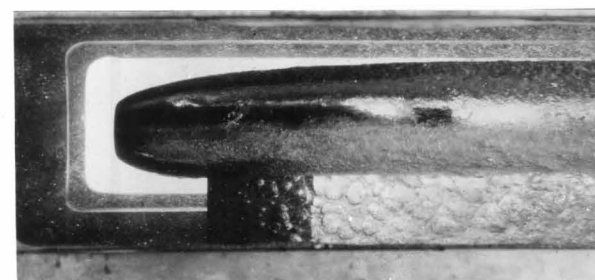
(b)

 $K = 0.44$

(c)

 $K = 0.39$

(d)

 $K = 0.36$

DEVELOPMENT OF CAVITATION BUBBLE

FIGURE 17

The appearance of some of the well advanced cavitation bubbles points to the existence of this gas circulation and pressure difference. Thus Figure 17 (a) to (d) shows the various stages in the development of cavitation on a projectile having a nose of low cavitation resistance. In the beginning the entire surface of the bubble appears milky or frothy and seems to be made up of a series of minute bubbles. It might be assumed that the entire space was filled with this froth. However, it must be remembered that rapid evaporation is taking place from the liquid through the interface into the gas space. The observer is looking from the liquid side and very probably sees only the breaking bubbles at the surface. Since the rate of entrainment at the downstream end of a cavitation zone is obviously high, the rate of evaporation is equally high in order to supply the required amount of gas. However, as the pressure decreases and the size of the bubble increases, the amount of the surface through which vaporization can occur appears to increase more rapidly than does the entrainment. This is shown by the fact that the forward part of the bubble begins to have glassy zones through which the projectile can be seen. As the bubble size increases further, this smoothing of the surface, i.e. the decrease in vaporization through it, spreads downstream until, as in the case of Figure 17 (d), the entire length of the projectile is visible. Now, if the pressure within the bubble were uniform, it would be expected that the rate of vaporization would be decreased uniformly over the whole interface. However, the photographs show that this is not the case and that the vaporization disappears first at the forward end of the bubble. The easiest explanation is the one previously offered, i.e., that the gas circulation has produced a slight pressure gradient with a higher pressure at the upstream end.

ENTRANCE BUBBLE

Enough has already been said concerning entrance and cavitation bubbles to indicate that the two phenomena belong to the same family. However, it is constructive to examine the specific points of similarity and difference between them.

COMPARISON OF ENTRANCE AND CAVITATION BUBBLES

If the two bubbles are compared on the basis of the cavitation parameter, K , it will be found that for the same value of K on a given projectile, the cavitation bubble and the entrance bubble will be of the same size and shape within reasonably close limits, i.e., they are geometrically similar. It must be remembered that in computing the value of K for the entrance bubble, the pressure of the air inside the bubble must be used for p_B , in place of the vapor pressure of the water. As the air pressure is much higher than the vapor pressure, a given value of K is obtained at much lower velocity for an air-filled bubble than for a true cavitation bubble. Since the bubbles are similar, the effect on the drag coefficient and on the coefficients of the other hydrodynamic forces should be the same for the two. It should be noted that force coefficients are specified rather than the forces themselves because the velocities involved for the same values of K are quite different in the two cases.

The gas supplies for the two cases are quite different. Although the cavitation bubble has an unlimited gas supply through the vaporization of the surrounding water, the entrance bubble has a very limited supply. When a projectile enters the water from the air, the supply of air to the bubble is cut off when the air tube to the surface closes. Henceforth, as the gas is pumped away through entrainment at the downstream end, either the bubble must get smaller or the pressure within it must drop. This process must continue until the bubble is completely consumed. However, for corresponding K 's the gas circulation and the entrainment should be comparable to that of the cavitation bubble. For the air bubble the interface will always be clear and transparent since no vaporization takes place across it.

Under some conditions the cavitation bubble can be considered a steady state phenomenon. For example, a projectile running at a constant depth and a constant velocity could maintain continuously a cavitation bubble corresponding to the existing value of K . The entrance bubble, on the other hand, is inherently transient because it has no continuous supply of gas. It is, of course, possible to imagine conditions on a torpedo in which the exhaust gases from the power plant could act as the source of supply. Likewise, the products of combustion from a jet-propelled torpedo

might furnish sufficient gas to maintain an entrance bubble. However, it appears that for the normal projectile shapes and arrangements, these points of discharge are not very favorable for the maintenance of the bubble. This is very fortunate, since it would be impossible to secure acceptable performance if a bubble large enough to envelop the body were maintained during the entire run.

ENTRANCE BUBBLE FORMATION

An examination of the cavitation parameter shows that at the point of passing through the interface, every projectile entering the water from the air is operating with a K of zero, since at that point $p_L = p_B$. Therefore, every projectile shape, no matter how excellent, must produce a bubble at water entrance. However, K rapidly assumes a finite value as the depth of submergence increases, even though an open passage is maintained from the projectile to the surface through which the air can continue to enter. This is because p_L always increases directly with the submergence.

Although the entire entrance phenomenon is transient in character, the changes that take place during the first diameter or two of travel after the projectile touches the water are so rapid that they introduce effects that are not significant during the rest of the life of the bubble. The initial accelerations imparted to the water are very high, and in the case of oblique entry the resistance to the flow is asymmetrical. Therefore, during this beginning part of the phenomenon, there is probably little similarity between the behavior of the entrance bubble and the bubble observed under steady state conditions. However, the flow pattern rapidly becomes established and the rates of change of the conditions decrease so that soon the differences between the transient and steady state conditions are not of major importance. Since this discussion is largely based on the results of experiments and analysis of steady state conditions, the conclusions are inherently limited to this second phase of the entrance phenomenon. It would seem that as a rough approximation this second phase might be thought of as beginning at about the time the projectile has traveled three or four diameters from the point of contact.

The entrance bubble is apparently formed for the same dynamic reasons that the cavitation bubble is formed. The water is forced out of the path of the moving projectile by the nose, thus giving the water a radial component of velocity. If the flow is to conform to the shape of the body, a point is soon reached when an acceleration must be produced towards the center of the body. If the pressure difference between the fluid and the surface of the body is not sufficient to produce this acceleration, then the flow will not follow the body surface. If there is a supply of gas available, the intervening space will be filled by it. This is, of course, what happens when the projectile enters the water. The water is forced away from the projectile and at the surface there is no restoring force; hence, only the forward part of the projectile is in contact with the water and the bubble forms aft of

this point. As the nose penetrates below the surface, the hydrostatic pressure builds up and acts to restrict the size of the bubble. It should be noted that the only force acting outward away from the projectile is supplied by the wetted portion of the nose. From this zone aft, the forces all act to produce an acceleration toward the body, thus tending to decrease and later to reverse the outward radial component. If the velocity of entrance is low, it is possible for the hydrostatic forces to close the bubble either on the mid or after section of the projectile. However, if the entrance velocity is increased, the hydrostatic forces will require a longer time to close the bubble. In this case the length of the bubble will be increased due to two factors, i.e., the bubble is open longer and also the projectile is going faster, thus creating more length of the bubble per unit time. Since the forces at the surface tending to cause closure are so low, it is normal that closure will take place at some point below the surface, and then a residual tube of air from the point of closure to the surface will be expelled, accompanied by considerable surface disturbance.

From the point of view of the above analysis, it will be seen that the maximum diameter of the entrance bubble for a given trajectory angle will depend upon two factors, (a) the shape of the nose and (b) the speed of the projectile. These control the magnitude of the outward acceleration and hence, the size of the bubble, since the restoring force, i.e., the submergence, is constant.

BUBBLE DECAY

The mass of air present in the entrance bubble reaches a maximum at the instant of its closure. From that point on, the bubble steadily loses gas to the surrounding fluid. In discussing the gas cycle within the cavitation bubble, it was pointed out that the downstream end of the bubble is a region of very rapid entrainment of the gas. This is equally true of the entrance bubble. The surrounding water acts as an ejector to pump the air out of the bubble by breaking off elements of it and carrying them away in the stream. Thus, the mass of gas continues to decrease. The volume of the bubble, however, is determined not only by the mass of the gas within it, but also by the pressure at which this mass is at equilibrium with the flow. This pressure, in turn, is a function both of the velocity of the projectile and the submergence, and, in addition, is affected by the shape of the nose. In short, it is governed by the value of K , just as was the case when the bubble was filled with water vapor. It will be seen that, if a projectile is submerged and running with constant velocity at constant depth within an entrance bubble, as the air is pumped out of the bubble the value of K will increase until the bubble disappears. There is one further assumption in this statement; namely, the value of K that is reached at the time that the last trace of air is entrained is greater than the K for incipient cavitation. If this is not the case, then the water will vaporize and the bubble will gradually turn into a pure cavitation bubble

-25-

in which the void is filled entirely by water vapor. In the case of high speed entry, it is very probable that this actually occurs, i.e., that the air-filled entrance bubble merges gradually into the vapor-filled cavitation bubble before the velocity is reduced sufficiently to eliminate the cavitation. Such a condition would be more apt to occur on a shallow-diving than on a deep-diving projectile, since, for similar velocity conditions, the latter projectile has a higher K .

If it is assumed that the projectile under consideration either is without power or is driven by propellers, the entrance bubble phase of the trajectory will be one of continually decreasing axial velocity. This decrease, in effect, acts as a compressing force on the air-filled bubble since it is tending to raise the value of K , and hence, to decrease the size of the bubble. If the submergence is increasing at the same time, this effect is accelerated. This compression alone probably tends to increase the mass rate at which the gas is pumped out of the bubble, simply because there is more mass carried away in a given volume of gas.

PROJECTILE DYNAMICS WITHIN CAVITATION AND ENTRANCE BUBBLES

There is a certain superficial similarity between the forces acting on underwater projectiles when enveloped in a bubble and the air flight of a similar projectile traveling at supersonic velocities. In both cases, assuming zero yaw, the principal force acts on the nose alone, and in general its point of application is well ahead of the center of gravity. Furthermore, in both cases the nose shape is of prime importance in determining the magnitude of the force for a given velocity. However, there is little point in pursuing this similarity very far since the mechanics of the two phenomena are quite different.

The forces on the projectile within the bubble are, as in the case for any other portion of the path, the result of the reaction from the change in momentum produced in the surrounding fluid by the presence of the projectile. Thus, if the movement of the water surrounding the projectile and its bubble were known, the projectile forces could be calculated. Since the surface of the bubble defines the path of the adjacent layer of water, the bubble shape can be used as an indication of the character of the flow. Since a change in the force on the projectile is the result of a change in the momentum imparted to the water by the projectile, such a change must be accompanied by a change in the bubble shape, i.e., in the path of the water adjacent to the bubble. Professor I.S. Bowen*, in investigating the performance of a certain special type of underwater projectile for Division 3 of the National Defense Research Committee, has stated that the bubble diameter at a given distance back of the head is an effective measure of the drag on the projectile, the force varying roughly as the diameter to the fourth power. This hypothesis assumes that the skin friction is negligible, since the wetted surface area is negligible, and that the drag force is directly proportional to the radial force imparted to the water to get it out of the way of the projectile. This latter statement implies a constant "efficiency" of the nose as a deflector, or in other words, all noses producing the same diameter of bubble are acted upon by the same force. This is probably true only within reasonable limits. For example, it would seem that in the case of a square nose, part of the axial force might be used to impart an appreciable axial component of velocity to the water; whereas, a long ogive, or fine ellipse might produce the same diameter bubble, but would impart practically no axial velocity to the liquid.

CROSS FORCE IN BUBBLE

In the preceding paragraph, the shape of the bubble was used as a basis for some of the conclusions regarding the drag. Bubble

* "Underwater Behavior of 3.5" Aircraft Rockets" Report CIT - JBC 23

-27-

shape is equally helpful in the investigation of the cross force. Thus, if the bubble is symmetrical, it is reasonable to suppose that the resultant force acts along the axis of symmetry of the bubble. If the axis of symmetry of the bubble coincides with the trajectory there should be no resultant cross force on the projectile. If the axis of the bubble makes an angle with the trajectory, then a cross force should be expected and its magnitude should be about equal to the drag force multiplied by the sine of the angle between the axes. In most cases, however, it will be observed that when the axis of the bubble does not coincide with the trajectory, the bubble is asymmetrical. For this case the bubble axis is not significant, so the resultant force must be used. This line of action is determined by the condition that in any plane containing this line, the amount of momentum change in this plane must be equal and opposite on each side of the line of action.

EQUILIBRIUM YAW ANGLES WITHIN ENVELOPING BUBBLES

Figure 18 is a diagrammatic sketch of the conditions which exist when a projectile is surrounded with a bubble, and is traveling with a pitch or yaw with respect to its trajectory. In the preceding paragraph it was pointed out that the cross force on a projectile is a function both of the force resisting the motion and the angle that the force makes with the trajectory. It will be seen from Figure 18 that this angle can be defined by two others: (a) the pitch or yaw angle of the projectile with the trajectory; (b) the inclination of the bubble axis or line of action with the projectile axis. It should be remembered in computing the cross force that the accepted definition is that the cross force is normal and the drag force is parallel to the trajectory, irrespective of the angle between the projectile axis and the trajectory.

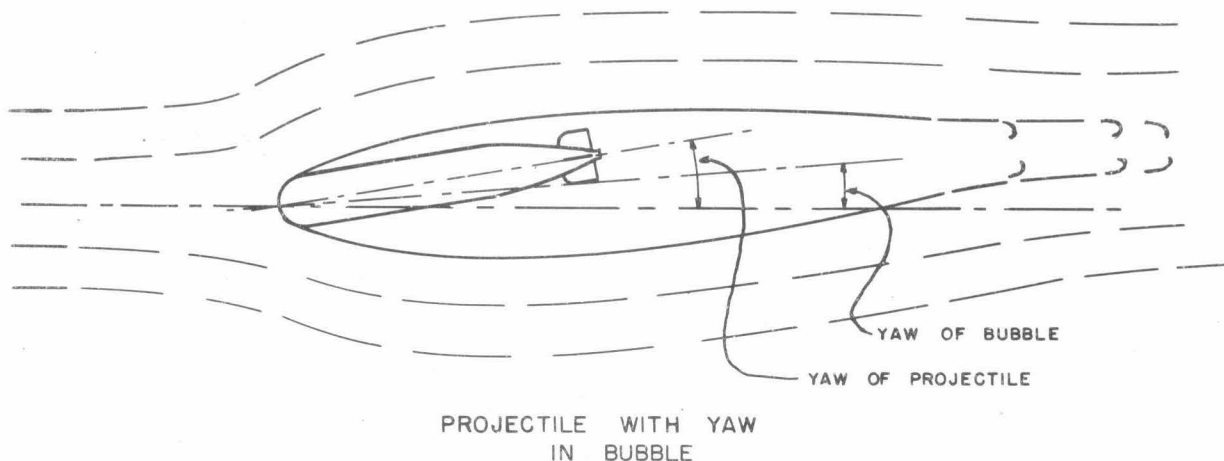


FIGURE 18

Some further simple deductions can be made concerning the forces acting on the projectile while it is surrounded by the bubble.

(a) The forces can act only on those portions of the projectile that are in contact with the water. Therefore, it is obvious that the moment produced by the hydrodynamic forces on the nose is usually a destabilizing one, since its point of application is always ahead of the center of gravity. Thus, unless the line of action of the nose force makes a greater angle with the trajectory than does the axis of the projectile, the resulting moment will be in a direction to increase the yaw.

(b) If the projectile is to be prevented from continuous rotation, a moment of equal and opposite magnitude must be applied to it. The forces which can produce such a moment first come into play when other points of the projectile touch the bubble interface. In projectiles of normal shapes the afterbody and the tail structure will be the points that will touch first. Since such points of contact lie well aft of the center of gravity, the moments resulting from the forces applied at these points are stabilizing.

(c) If the stabilizing moment from these forces increases faster with increasing yaw than does the destabilizing one from the nose force, an equilibrium yaw angle can be reached at which these two moments will be balanced. Since, however, under these conditions the cross forces will not balance, the projectile will be forced into a curved path. If this condition persists long enough to obtain equilibrium, the radius of curvature of the path will be such that the centrifugal force just balances the hydrodynamic cross force.

RELATION BETWEEN SIZE OF BUBBLE AND EQUILIBRIUM YAW ANGLE

Some qualitative conclusions can be drawn concerning the interaction between the various parts of the projectile:

(a) Other things being equal, the curvature of the path will depend upon the magnitude of the cross force.

(b) For a given nose and location of center of gravity, the cross force will depend on the equilibrium angle of yaw and the distance aft from the center of gravity to the points at which the forces are applied that furnish the stabilizing moment.

(c) From this it follows that the longer the afterbody and the larger the diameter of the tail structure, the greater will be the radius of curvature, or, in other words, the less will be the deviation of the projectile from a straight path. The reasoning is as follows: The bubble size and shape is a function of the nose shape alone. Therefore, for a yawing projectile, the farther aft the afterbody and tail structure extends from the center of gravity, the sooner it will come in contact with the wall of the bubble. Thus, the longer the afterbody and tail, the smaller will

be the equilibrium angle and the less will be the cross force on the nose. Furthermore, the amount of tail cross force required to produce the necessary stabilizing moment will decrease as the points of contact of the afterbody and tail move aft.

(d) The same line of reasoning leads to the statement that the radius of curvature of the path of a projectile of given construction can be changed simply by changing the shape of the nose. Two factors enter into this: the size of the bubble produced and the amount of cross force for a given yaw. Thus, if a change in the nose is made which results in a larger bubble but leaves the relationship between cross force and yaw unchanged, the effective cross force at equilibrium will, nevertheless, increase. This is because the projectile will have to rotate to a larger yaw angle before the afterbody and tail come in contact with the bubble surface and are forced into it far enough to develop the moment required to balance the destabilizing moment of the nose. This larger yaw angle means a greater cross force on the nose; likewise, a greater cross force on the tail, and hence, a shorter radius of curvature to produce the centrifugal force required to balance this larger cross force. The result would be the same if the nose were changed in such a manner that the size and shape of the bubble would be unaffected, but that the resulting cross force would be larger for a given yaw angle. In general, it is very difficult to modify the bubble shape without affecting the cross force and vice versa, since, as previously pointed out, the bubble shape and the nose forces are intimately related.

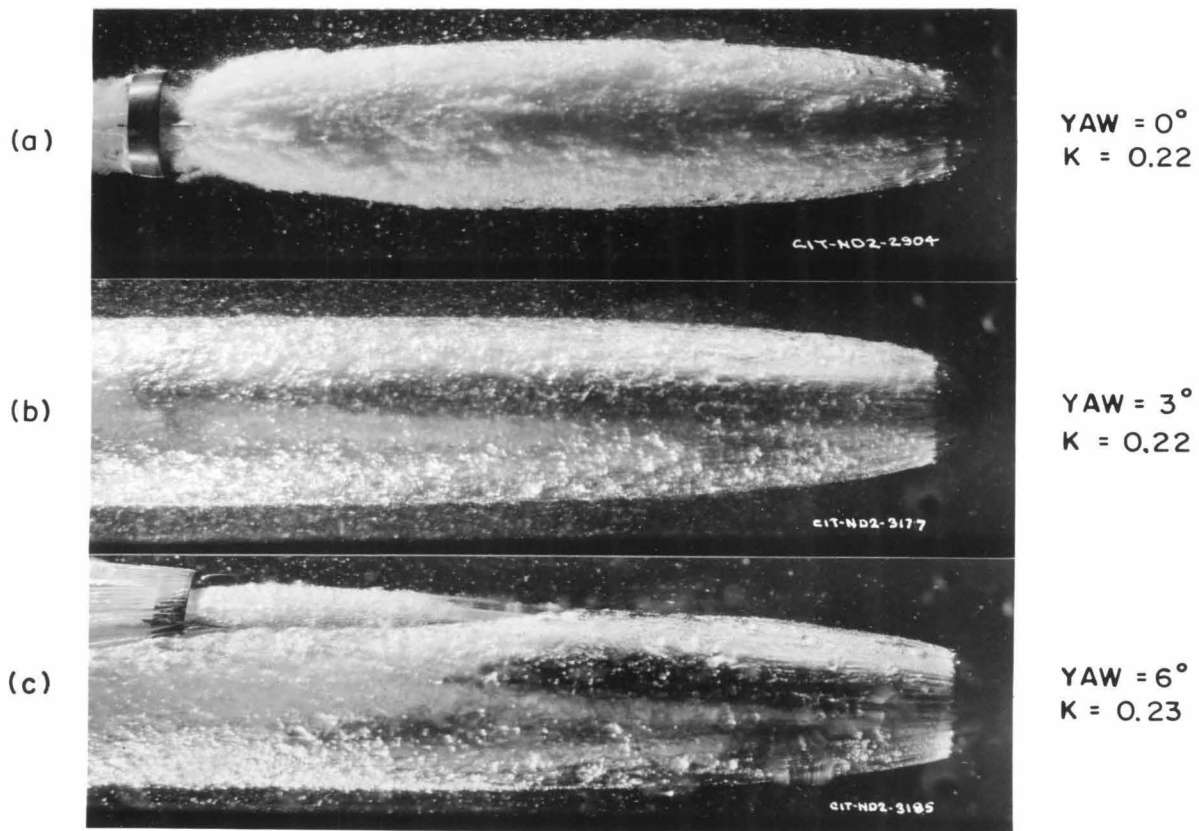
(e) It will be seen from the interrelation of these factors that any change in the design of a given projectile that affects (1) the shape of the nose, (2) the shape of the afterbody and tail surfaces, and (3) the position of the center of gravity, will result in a change in the performance of the projectile while it is in the bubble stage. Conversely, when the relative behavior of these various factors is known and understood, it may be possible to design a projectile with any desired behavior in the bubble phase.

CHARACTERISTICS OF SPECIFIC NOSE SHAPES

Very little quantitative information is available concerning the characteristics of various nose shapes. However, at the present time a few comments can be made concerning the following specific shapes:

HEMISPHERICAL NOSES

If the bubble produced by a hemispherical nose is observed from its inception until it develops to a length of many times that of the projectile, it will be seen that when it first appears



HEMISPHERICAL NOSE
FULL CAVITATION WITH YAW

FIGURE 19

-34-

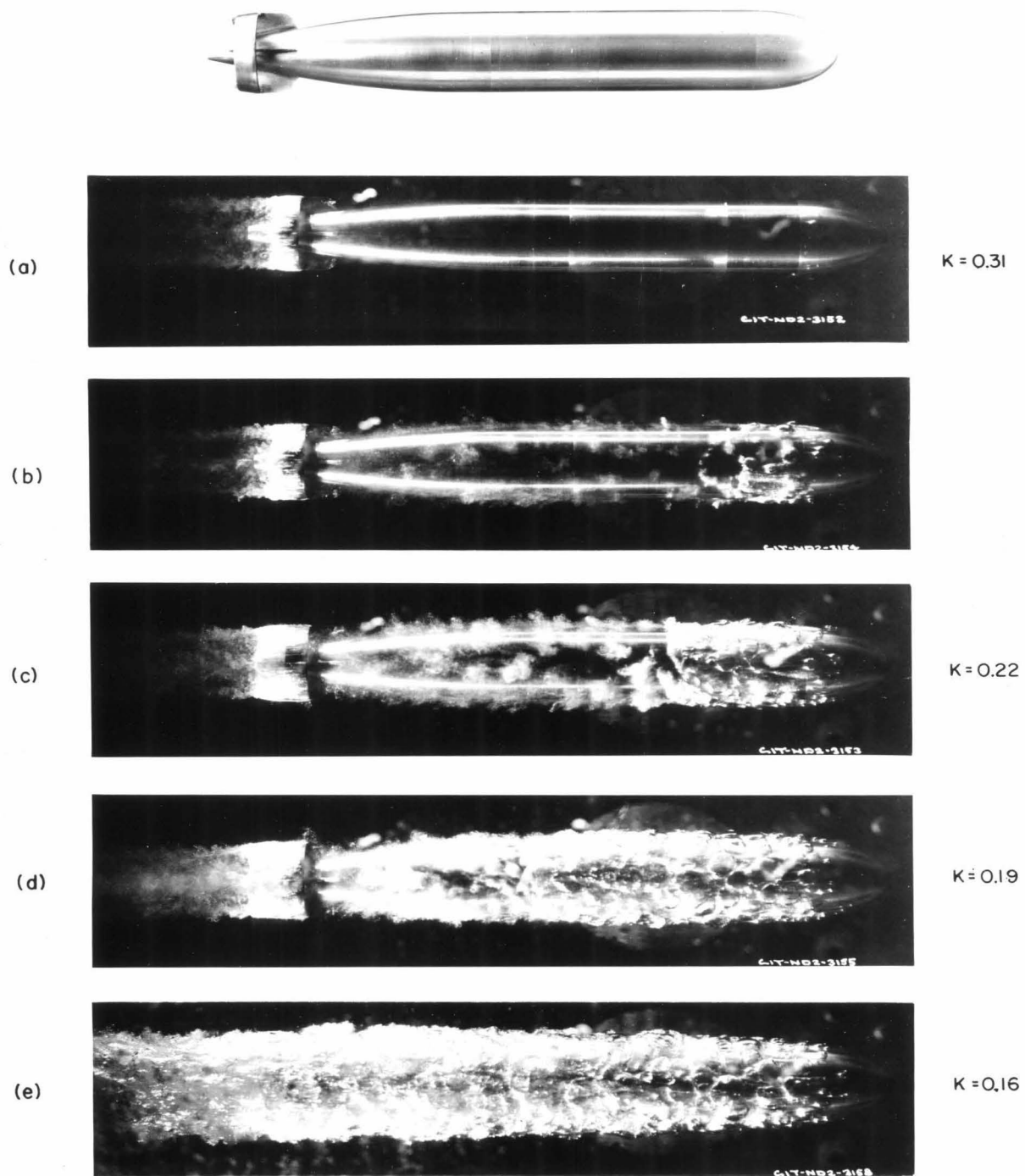
it is located nearly at the junction between the hemisphere and the cylinder. As it grows longer and longer, the point at which it springs clear from the nose slowly moves forward until, when the bubble is fully developed, it leaves the hemisphere considerably forward of the point of tangency of the sphere with the cylinder. This is clearly shown in Figure 12. If, when the bubble is fully developed, the projectile within it is yawed a few degrees, the shape of the surface in contact with the water is unaltered since it always remains a segment of a sphere. Figure 19 (a) to (c) shows this behavior. Note especially that the line of contact of the bubble with the projectile always remains perpendicular to the direction of flow, that is to the trajectory. This property of preserving the same contact surface, independent of the pitch or yaw angle, is unique to the sphere. The result is that the bubble is unaffected in shape or alignment with the trajectory by moderate pitches or yaws, and consequently, the resultant force on the projectile is unchanged in magnitude and direction with respect to the trajectory. Hence, for small angles the cross force is zero and the moment is linearly proportional to the yaw.

ELLIPSOIDAL NOSES

If the development of the bubble on a projectile with an ellipsoidal nose is observed in the manner just described, it will be seen that the superficial behavior is similar, i.e., as the bubble grows, its point of contact moves forward on the nose. However, in the case of the ellipsoid, the amount of forward movement is considerably greater than that on the hemisphere. This movement can be observed in figure 20. If, while the bubble is fully developed the projectile is again yawed slightly, it will be seen that the wetted surface becomes asymmetrical and causes the bubble to alter its shape and alignment. This change appears to be in the direction to increase the cross force and the moment, largely as the result of swinging the axis of the bubble. Figure 21 shows top views of the cavitating nose shape seen in Figure 20. Compare the bubble shapes with and without yaw. Note particularly that with the elliptical nose, the line of contact of the bubble with the projectile swings from being perpendicular to the flow at zero yaw, to a deviation from perpendicular of from two to three times the yaw at 6° yaw, and that this rotation is in the opposite direction to that of the yaw.

OGIVES

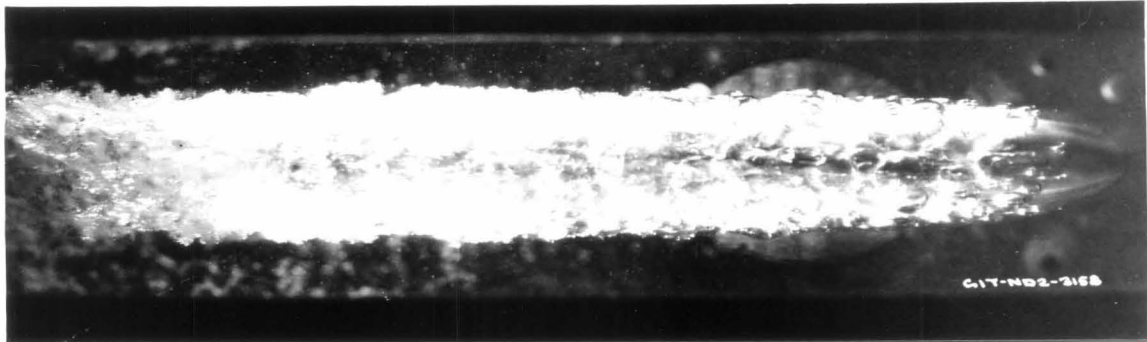
The behavior of simple ogives, i.e., nose shapes generated by the rotation of an arc of a circle which is tangent to the cylinder, is about the same as that of the family of ellipsoids. Other nose shapes which are "finer" than the hemisphere, have a similar type of behavior, i.e., the cross forces and moments appear to increase more rapidly with yaw than they do with the hemisphere.



DEVELOPMENT OF CAVITATION
2:1 ELLIPSOIDAL NOSE

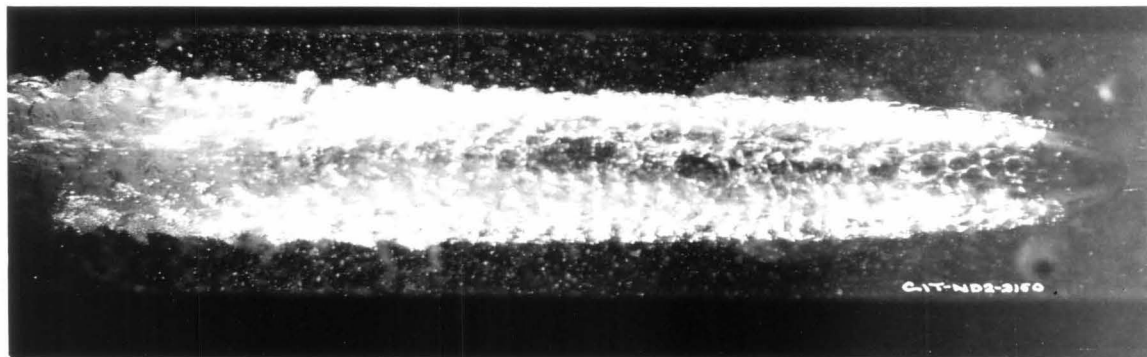
FIGURE 20

(a)



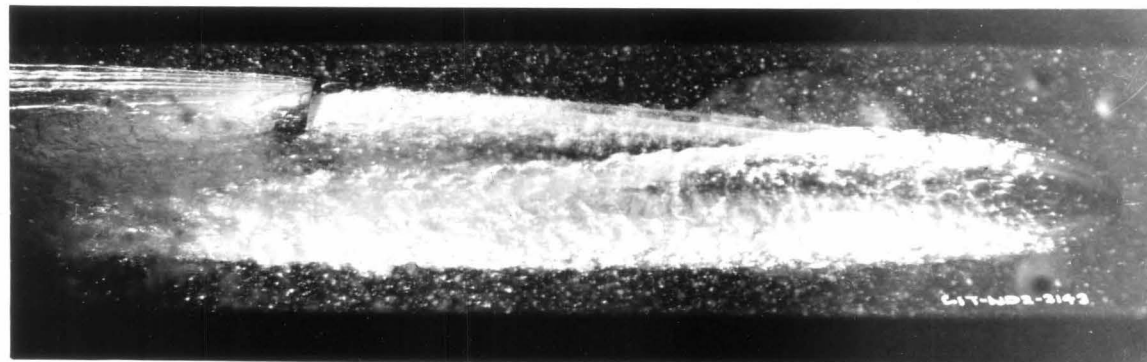
$K=0.16$
 $\psi=0^\circ$

(b)



$K=0.17$
 $\psi=3^\circ$

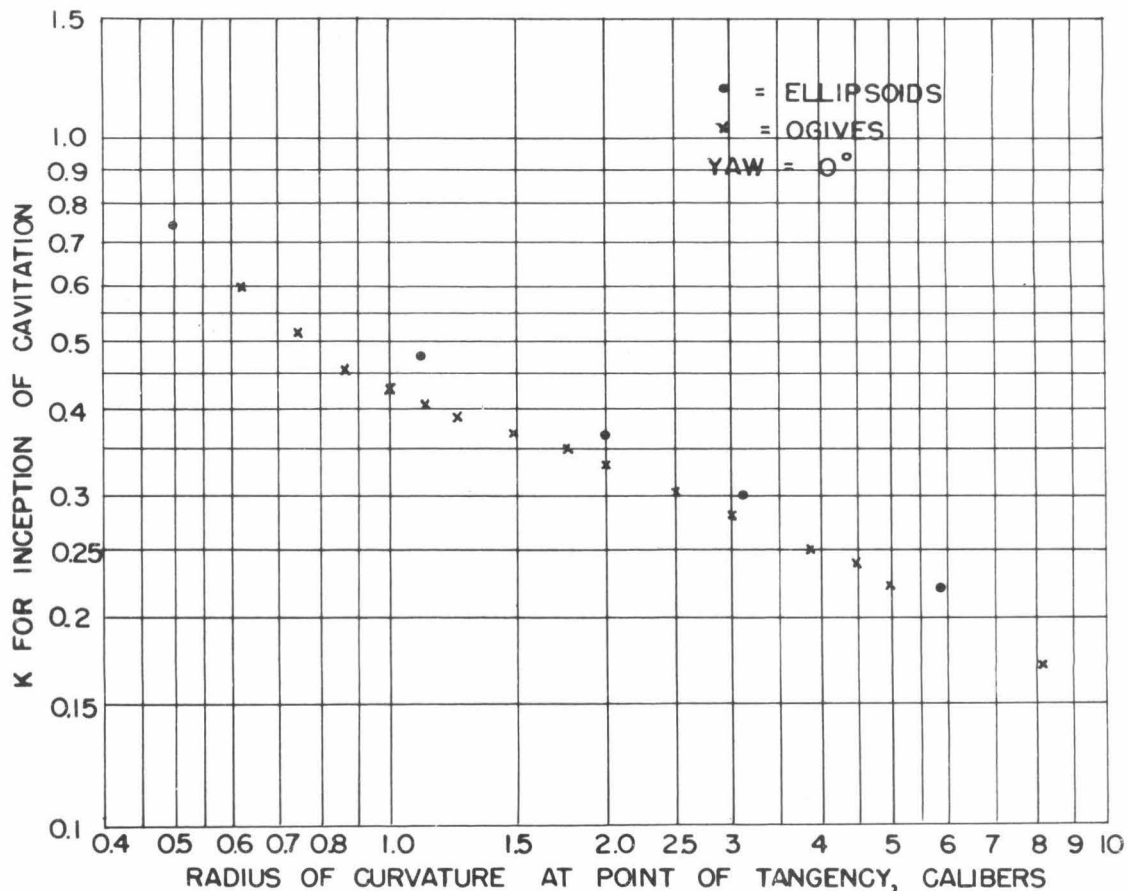
(c)



$K=0.17$
 $\psi=6^\circ$

FULL CAVITATION WITH YAW
2:1 ELLIPSOIDAL NOSE

FIGURE 21



CAVITATION PARAMETER VS. CURVATURE

FIGURE 22

RESISTANCE OF NOSES TO INCEPTION OF CAVITATION

The resistance of many nose designs to the inception of cavitation appears to depend upon the radius of curvature of the nose at the point of tangency with the cylindrical portion of the body. Apparently, cavitation follows the laws of geometrical similarity. This means that the radius of curvature must be measured in relative rather than in absolute units, i.e., in calibers or diameters of the body. For simple shapes, such as ogives and ellipsoids, the greater the radius of curvature at the point of tangency, the higher will be the cavitation resistance, i.e., the lower will be the parameter, K , at the inception of cavitation. Figure 22 shows the results of the experimental determination of K for inception on various ellipsoids and ogives. It should be noted that although these two series of shapes look quite different, the K 's are about the same for equal curvatures at the point of tangency.

ENTRANCE BUBBLE AND CAVITATION PERFORMANCE CHARACTERISTICS FOR
SUCCESSFUL OVERALL FLIGHT

In much of the previous discussion very little attempt has been made to distinguish between the characteristics of the entrance and the cavitation bubbles. The primary reason for this lack of distinction is, of course, that they are felt to be two aspects of the same phenomenon. However, in considering the overall trajectory, it must be remembered that generally speaking, if both manifestations occur, they are not concurrent, but appear one after the other. Therefore, it is necessary to examine the projectile shape from two separate viewpoints, i.e., to see if it will give satisfactory performance (a) in the entrance bubble, and (b) in the subsequent underwater run.

At first sight it might appear that the best entrance bubble would be none at all. However, the previous discussion has shown that at the water surface every nose shape will form an entrance bubble, that it is very difficult to design the nose so that at a given speed this bubble will be exactly the size of the projectile, and that even if this were achieved for one speed, the bubble would be longer and larger as the speed was increased. Furthermore, the entrance bubble may serve the very useful purpose of increasing the curvature of the path in the vertical plane so as to reduce the maximum depth of dive and shorten the distance from the point of entrance to the beginning of the normal part of the run. Satisfactory performance in the bubble phase must include the following items:

- (1) The decelerating force, and hence, the drag in the bubble, must be kept below the point at which structural damage occurs.
- (2) The torpedo must remain "on course" in the horizontal plane.
- (3) The combination of the cross force and the pitch in the bubble must result in a curvature which prevents deep dives, but does not permit broaching.

The most desirable cavitation characteristics for a torpedo or similar projectile is that cavitation should occur on no part of it during its normal steady state run. If this is impossible to achieve, then if satisfactory performance is to be obtained, the cavitation effects must stay within the following limitations:

- (1) The drag must not be increased appreciably.
- (2) The change in the cross force and moment must not affect the stability adversely.
- (3) The cavitation must not blanket or reduce appreciably the effect of the control surfaces.
- (4) The propulsive efficiency must not be reduced.

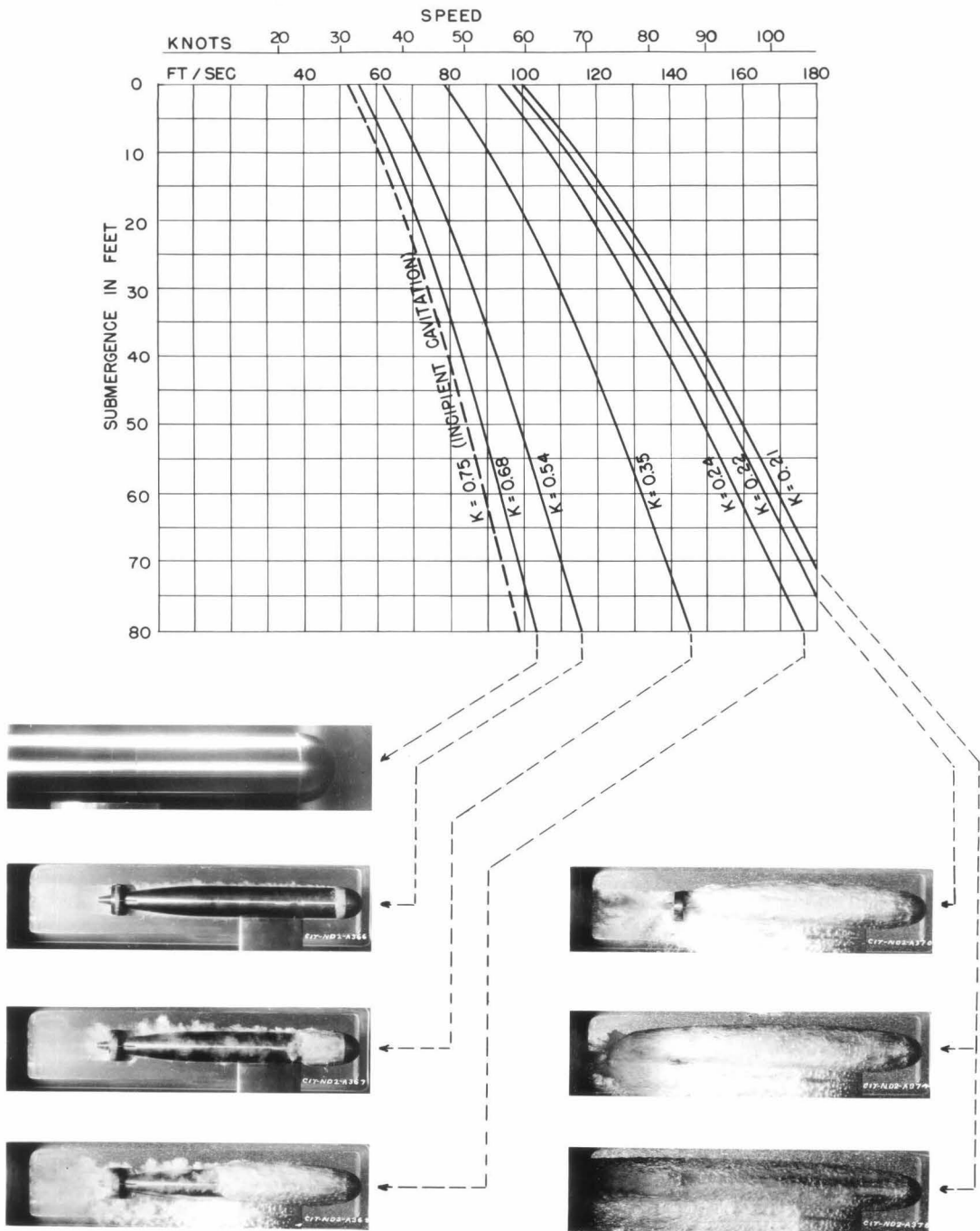
These limitations mean essentially that if cavitation does occur, it must be extremely limited, especially in the regions of the control surfaces and propellers.

SELECTION OF NOSE SHAPE FOR SATISFACTORY OVERALL PERFORMANCE

A review of the discussion of the effect of nose shape on the performance within the entrance bubble indicates that, in general, the "fine" noses, such as long ellipsoids, ogives, etc., produce such high cross forces that the projectile is very hard to control while in the bubble, is liable to "broach" badly, and on the other hand, may make deep dives if at the water entry point there is an appreciable down pitch. These undesirable characteristics may be alleviated by increasing the effective length of the projectile, either by actually lengthening the body or by applying a shroud ring to the tail. However, hemispherical or "near" hemispherical noses show more desirable entry characteristics, particularly for small entry angles. Further improvement appears possible by using even blunter shapes. On the cavitation side of the picture conditions are exactly the reverse. The finer the nose, the better the cavitation resistance. It will be seen from Figure 23 that cavitation begins to appear on the hemispherical nose at 50 knots and 40 feet submergence, and increases rapidly if either the speed is increased or the submergence decreased. Blunter noses show even poorer performance. It is obvious that the hemispherical nose is not satisfactory for a modern high speed torpedo, and it can be anticipated that future requirements will call for even higher speeds and lower minimum submergences. It thus appears that the nose shape requirements for satisfactory performance within the entrance bubble and satisfactory cavitation performance during the normal run are diametrically opposed.

SPHEROGIVE NOSES

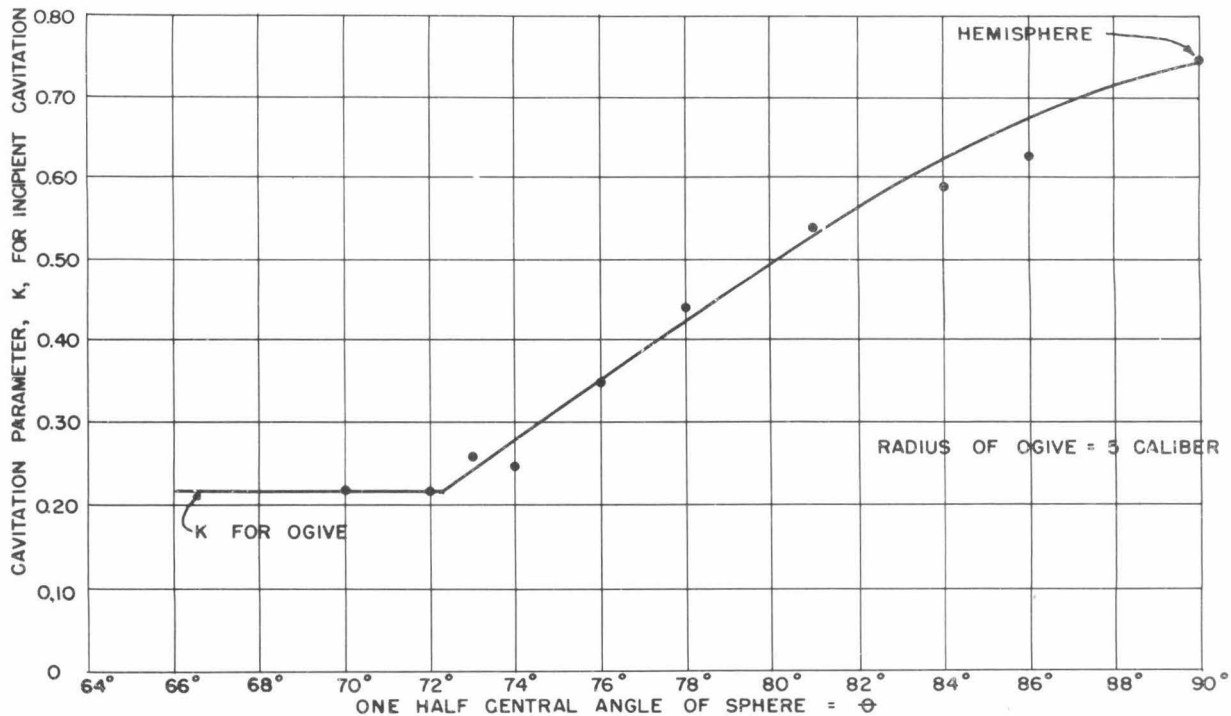
One promising approach to the problem of satisfying simultaneously these conflicting requirements has been made by this laboratory. This is in the development of the so-called "spherogive" nose, i.e., a nose shape which consists of a tip formed by a segment of a sphere and a transition section which consists of a single radius ogive tangent to the sphere and to the cylindrical section of the projectile. This shape was investigated first to see if it offered a simple substitute for an ellipsoid. However, a series of measurements showed that it possessed some unique cavitation characteristics. For example, Figure 24 shows the performance of a family of spherogives constructed in accordance with the outline drawing of Figure 25. It will be seen that in the entire family the transition ogive has a constant radius. The only difference occurs in the radius and angle of the spherical segment which forms the tip. It will be observed that from the viewpoint of cavitation resistance as measured by the K for incipient cavitation, there is no significant difference between performance of the simple pointed ogive and all of the spherogives in this particular family in which the spherical tip has a half angle of 74 degrees or less. However, when the spherical tip



HEMISPHERICAL NOSE
CAVITATION DEVELOPMENT RELATED TO DEPTH
AND SPEED

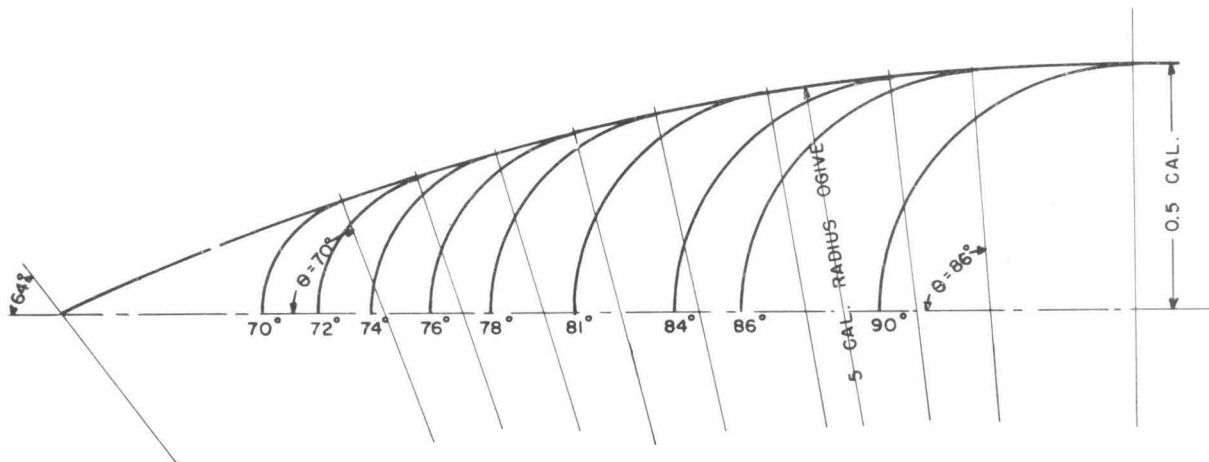
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FIGURE 23



FAMILY OF 5 CALIBER SPHEROGIVES
CAVITATION PARAMETER VS. ANGLE OF SPHERE

FIGURE 24



FAMILY OF 5 CALIBER SPHEROGIVES

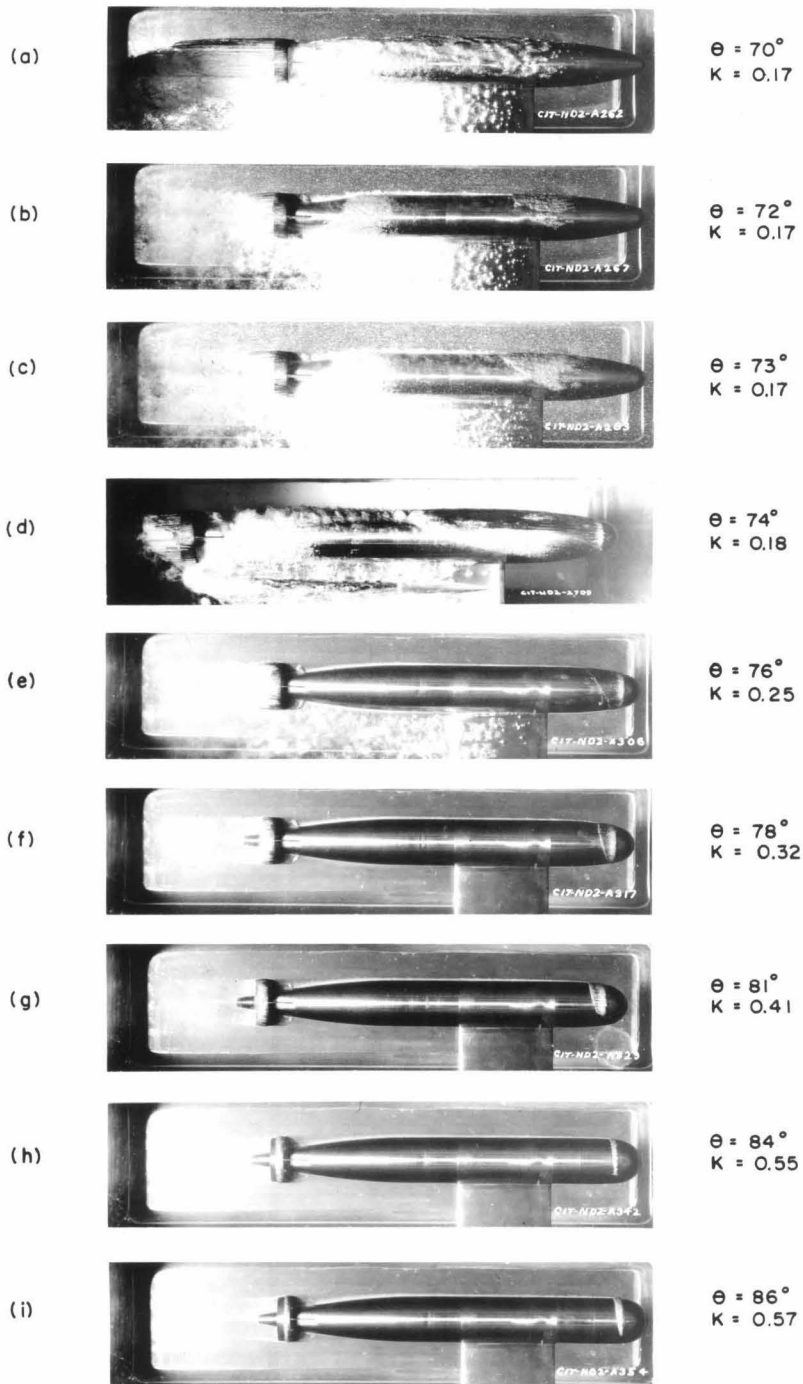
FIGURE 25

exceeds 74 degrees, the cavitation resistance continues to decrease, reaching the value of the hemisphere when the central angle is 90 degrees. Figure 26 shows the appearance of these various noses while cavitating. For all of the series with tips smaller than 74 degrees, cavitation starts at the point of tangency with the ogive of the cylinder. For all the members having spherical tips larger than 74 degrees, cavitation starts on the sphere; whereas, for the member having the spherical tip of 74 degrees, cavitation appears simultaneously on the sphere and at the point of tangency with the cylinder. One further item should be noted. All of the members of the series had better cavitation resistances than the hemisphere, and all of those having tips of 77 degrees or less had very good cavitation resistance. For example, they could all operate without cavitating under such severe conditions as a speed of 50 knots and 10 feet submergence.

Now a reference to the discussion concerning the characteristics of the hemispherical nose in the cavitation bubble shows that its good performance is attributed to the fact that the line of action of the force with respect to the flow was unaffected by small angles of pitch or yaw because the shape of the nose in contact with the water and, hence, the shape of the bubble was unaltered by the change in angle. Thus it would appear possible for a properly designed spherogive to have good performance both within the entrance bubble and also during the subsequent steady state running conditions. In the series under discussion, spherogives having tip angles between 72 degrees and 77 degrees would seem to offer good possibilities, since the cavitation bubble, and hence, the entrance bubble, always leaves the nose from a point on the spherical tip. Under these conditions the projectile should be insensitive to pitch and yaw; whereas, for steady state running conditions there should be no cavitation on the nose for any speed below 50 knots at submergence greater than 10 feet.

One further physical factor has to be considered. If the projectile is to be insensitive to yaw or pitch while in the entrance bubble, the bubble must be large enough so that it does not touch the body of the projectile at any point, after leaving the spherical tip, until it reaches the afterbody or the tail. This means that the bubble produced by the spherical tip must have a diameter larger than that of the projectile. Now, it is possible to have a spherogive tip so designed that cavitation starts on the sphere, but that the sphere is so small that the bubble produced by it will not be as large as the diameter of the projectile. Hence, the bubble will touch on the ogive part of the nose and thus be opened out to an adequate diameter. If this happens, the insensitivity to yaw is forfeited.

Model and full-scale experiments are being carried out in cooperation with the Morris Dam Torpedo Launching Range to determine whether or not these concepts are valid. It is, of course, realized that the spherogive is probably not the best shape that can be constructed which will satisfy the conflicting requirements

$\theta = \frac{1}{2}$ CENTRAL ANGLE
OF SPHERE


FAMILY OF 5 CALIBER SPHEROGIVE CAVITATION PHOTOGRAPHS

FIGURE 26

of the entrance bubble and the cavitation characteristics. Certainly the ogive section can be improved, for example, by substituting a curve of continuously changing curvature which has infinite curvature at the point of tangency with the cylinder. Improved characteristics may also be obtained by modifying the spherical tip to produce even less change in moment with pitch or yaw. However, the basic principle involved, namely, securing a good cavitation resistance by making the overall shape of the nose effectively "fine" while, at the same time, designing the forepart so that the wetted surface at the head of the bubble has the correct shape for satisfactory bubble performance, seems to hold much promise for future developments.